
The US Long Baseline Neutrino Experiment Study - 1

*Plenary Meeting of the International Design Study for the Neutrino Factory,
CERN, Mar 29-31, 2007*

Mary Bishai (BNL)

mbishai@bnl.gov



U.S. Long Baseline ν Study

The Chairs: Sally Dawson (BNL) and Hugh Montgomery (FNAL).

Advisory Committee: Franco Cervelli (INFN) Milind Diwan (BNL); co-leader, Maury Goodman (ANL), Bonnie Fleming (Yale), Karsten Heeger (LBL), Takaaki Kajita (Tokyo), Josh Klein (Texas), Steve Parke (FNAL), Gina Rameika (FNAL); co-leader

The Charge: Compare the neutrino oscillation physics potential of (report to NuSAG):

1) A broad-band proposal using either an upgraded beam of around 1 MW from the current Fermilab accelerator complex or a future Fermilab Proton Driver (PD) neutrino beam aimed at a DUSEL-based detector (Water Cerenkov and/or Liquid Argon). [this talk]

2) Off-Axis next generation options using a 1-2 MW neutrino beam from Fermilab and a liquid argon detector as a second detector for the NOVA experiment. [Niki Saoulidou's talk]

Status: Documents at <http://nwg.phy.bnl.gov/fNAL-bNL/>

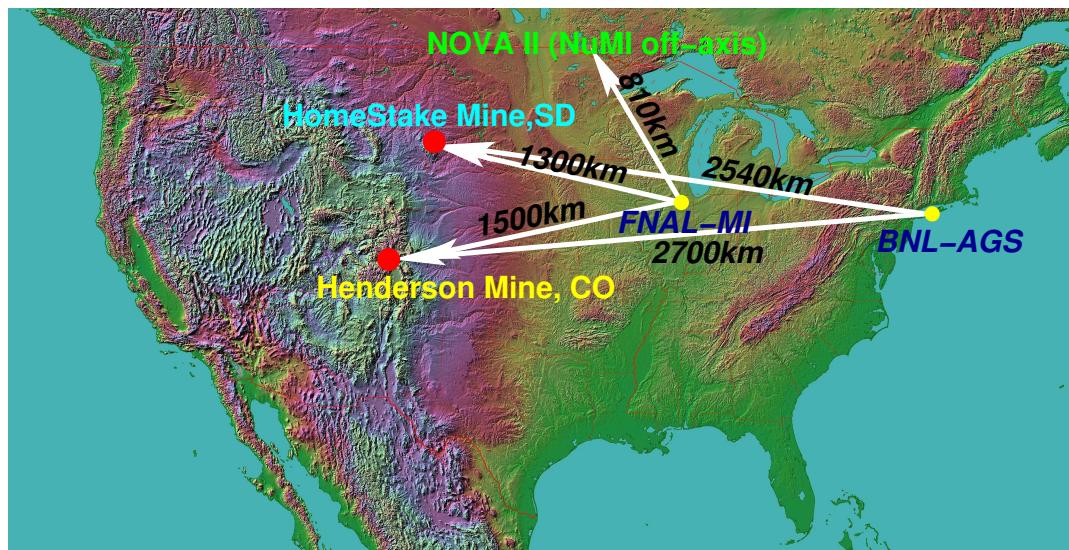
BEAM SPECIFICATIONS AND DESIGNS

"Fermilab Proton Projections for Long-Baseline Neutrino Beams," Robert Zwaska for the SNuMI planning group, July 17, 2006. FNAL-Beams-DOC-2393

"Target System for a Long Baseline Neutrino Beam," N. Simos, H. Kirk, J. Gallardo, S. Kahn, N. Mokhov. June 26, 2006.

"Simulation of a Wide-band Low-Energy Neutrino Beam for Very Long Baseline Neutrino Oscillation Experiments," M. Bishai, J. Heim, C. Lewis, A. D. Marino, B. Viren, F. Yumiceva, July 20, 2006

Beam Options/Baselines



The following beam options and baselines are considered:

Off axis beams using the 120 GeV NuMI beamline at FNAL to sites at 810km.

A 28 GeV on-axis Wide-Band Beam (WBB) beam from the BNL AGS to DUSEL sites at 2540 and 2700 km.

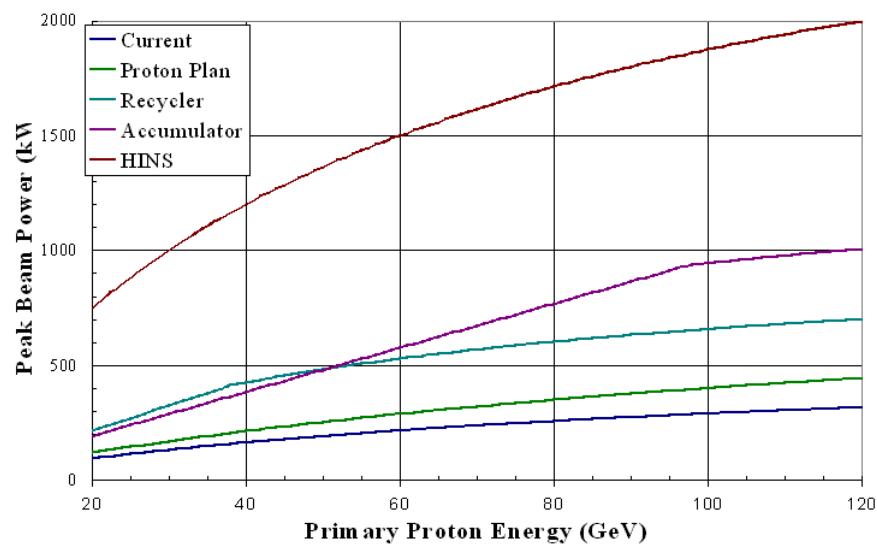
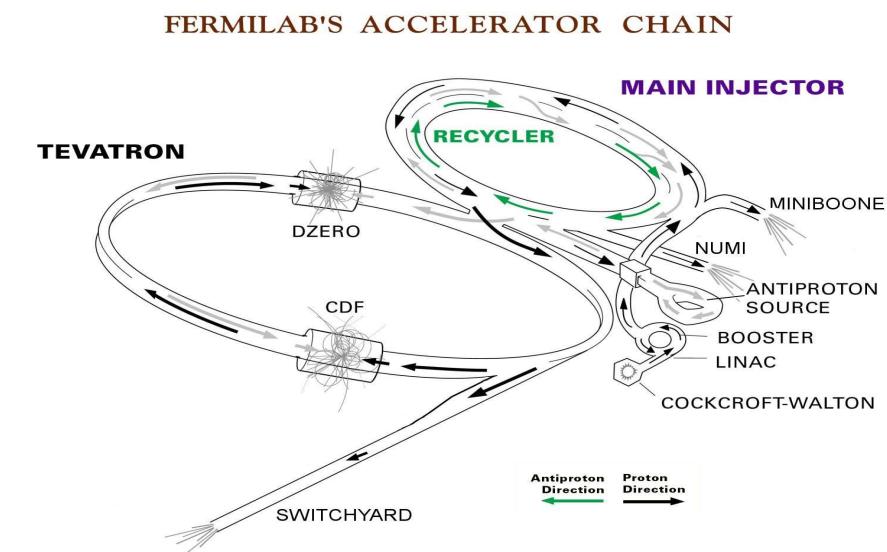
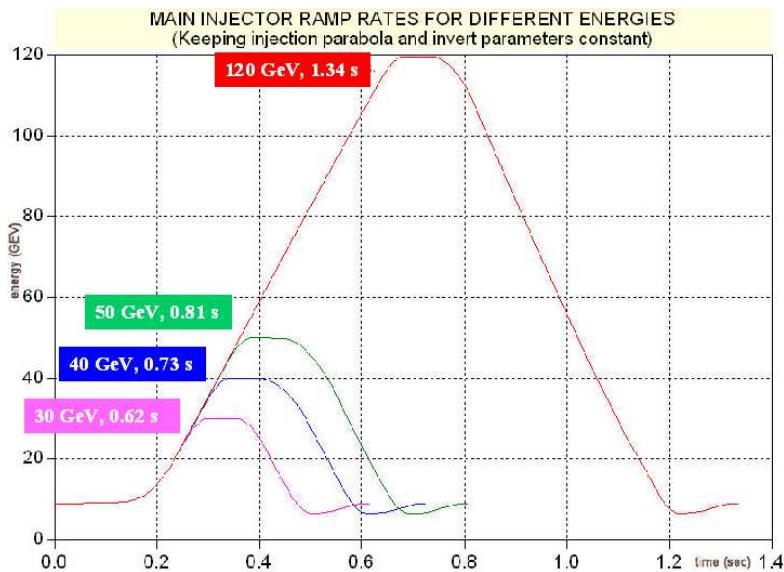
A newly designed on-axis \leq 120 GeV Wide Band Low Energy (WBLE) beam and beamline from the FNAL MI to DUSEL sites at 1300km and 1500km.

For the current study we will concentrate on beam options from FNAL

FNAL Beam Specs: E & Power

Incremental upgrades possible
(no proton driver):

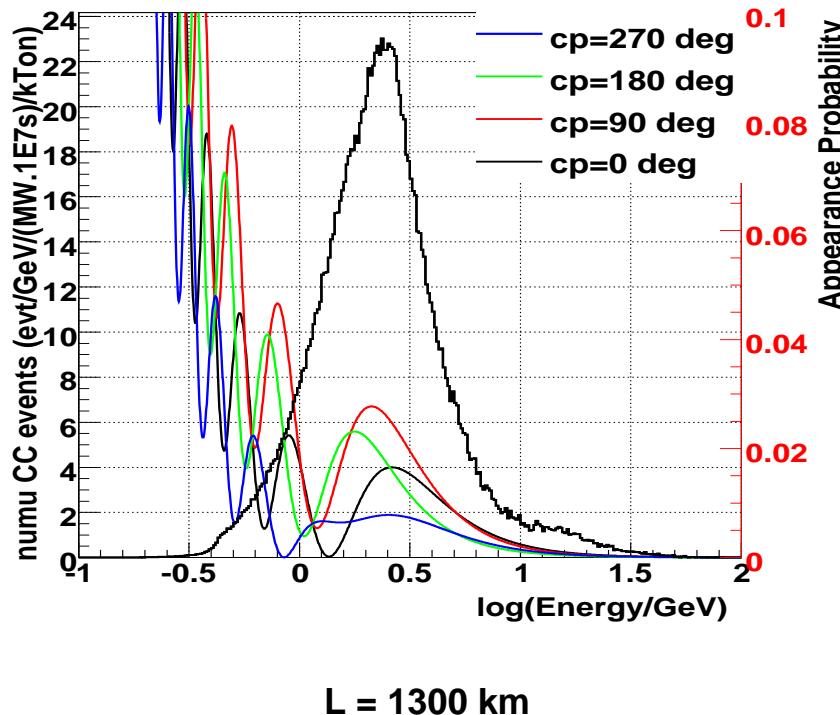
Use the existing recycler and anti-proton accumulator to store protons from the 8 GeV 15 Hz Booster during the MI cycle then inject to MI bringing intensity up to $6 \times 10^{13} p/\text{spill}$.



WBLE Beam Design Requirements

The design specifications of a new WBLE beam based at the Fermilab MI are driven by the physics of $\nu_\mu \rightarrow \nu_e$ oscillations:

WBLE 120 GeV, CC rate, sin²theta13=0.02, at 1300km, 12km off-axis



Requirements:

- Maximal possible neutrino fluxes to encompass the 1st and 2nd oscillation nodes, with maxima at 2.4 and 0.8 GeV.
- High purity ν_μ beam with negligible ν_e

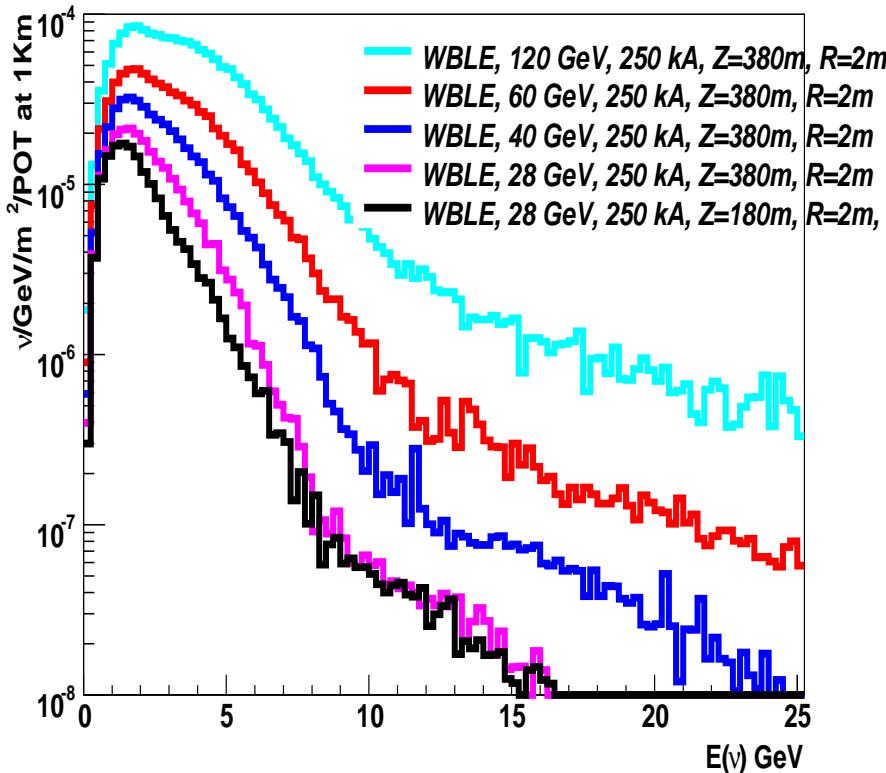
-Minimize the neutral-current feed-down contamination at lower energy, therefore minimizing the flux of neutrinos with energies greater than 5 GeV where there is no sensitivity to the oscillation parameters is highly desirable.

WBLE Beam Spectra for VLBNO

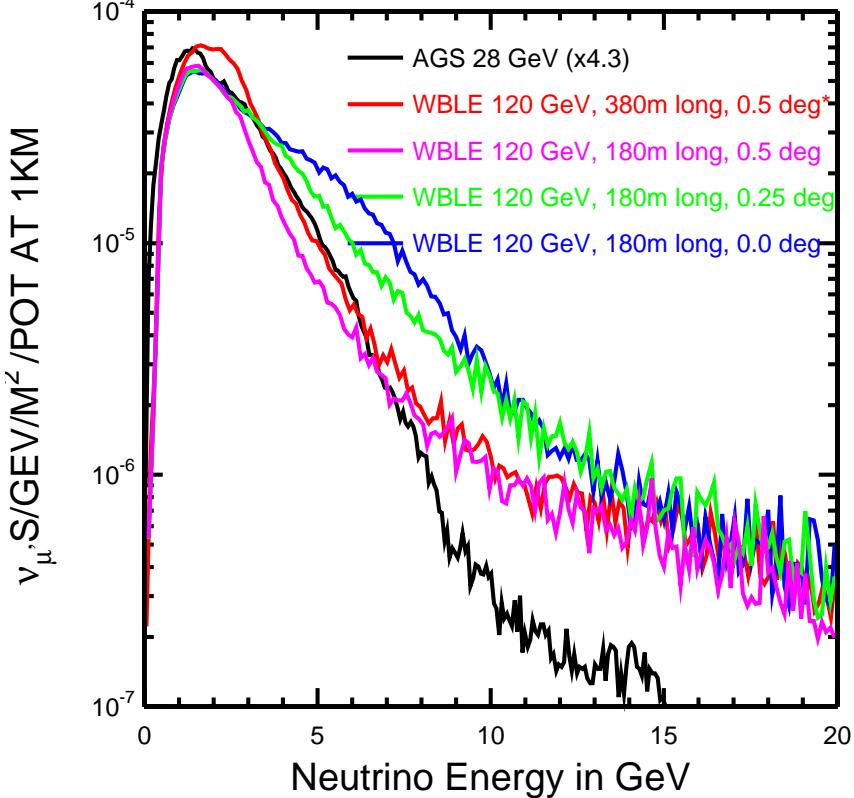
Decay pipe radius chosen to be 2m = the maximum that can be accommodated in FNAL rock with concrete shielding for a MW class beam.

Siting restrictions at FNAL \Rightarrow decay pipe is ≤ 400 m in length

WBLE beam, different energies, decay tunnels



WBLE 120 GeV beam, different off-axis angles, decay tunnels



GEANT 3.21 simulation of wide-band horns+decay pipe, with FLUKA '05 for target hadro-production.

Based on NuMI simulation which matches observed MINOS event rate to 10% in 0 - 7 GeV range

ν_e Appearance Rates

$$\Delta m_{21,31}^2 = 8.6 \times 10^{-5}, 2.5 \times 10^{-3} \text{ eV}^2, \sin^2 2\theta_{12,23} = 0.86, 1.0$$

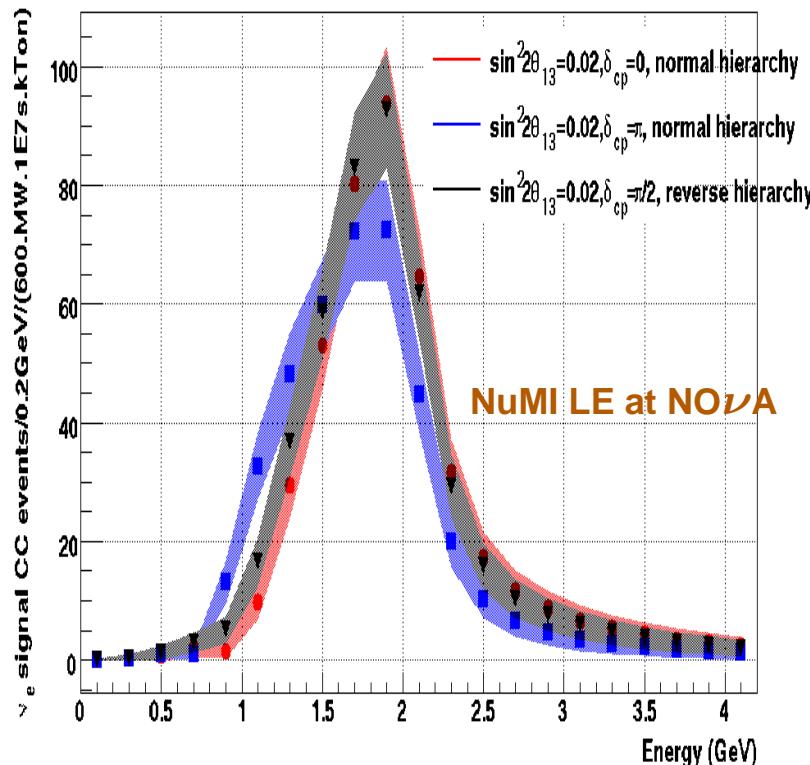
| | | $\nu_\mu \rightarrow \nu_e$ rate | | | | $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ rates | | | | |
|--|-----------------------|----------------------------------|------|------|------|---|------|------|------|--|
| (sign of Δm_{31}^2) | $\sin^2 2\theta_{13}$ | δ_{CP} deg. | | | | | | | | |
| | | 0° | -90° | 180° | +90° | 0° | -90° | 180° | +90° | |
| NuMI LE beam tune at 810km, per 100kT. MW. 10^7 s | | | | | | | | | | |
| 15 mRad off-axis (NO ν A) | | Beam ν_e = 43* | | | | Beam $\bar{\nu}_e$ = 17* | | | | |
| (+) | 0.02 | 76 | 108 | 69 | 36 | 20 | 7.7 | 17 | 30 | |
| (-) | 0.02 | 46 | 77 | 52 | 21 | 28 | 14 | 28 | 42 | |
| 50 mRad off-axis | | Beam ν_e = 11* | | | | Beam $\bar{\nu}_e$ = 3.4* | | | | |
| (+) | 0.02 | 5.7 | 8.8 | 5.1 | 2.2 | 2.5 | 1.6 | 0.7 | 3.3 | |
| (-) | 0.02 | 4.2 | 8.0 | 5.7 | 2.0 | 2.3 | 2.2 | 0.8 | 3.6 | |
| WBLE 120 GeV beam at 1300km, per 100kT. MW. 10^7 s | | | | | | | | | | |
| 9 mRad off-axis | | Beam ν_e = 47** | | | | Beam $\bar{\nu}_e$ = 17** | | | | |
| (+/-) | 0.0 | 14 | N/A | N/A | N/A | 5.0 | N/A | N/A | N/A | |
| (+) | 0.02 | 87 | 134 | 95 | 48 | 20 | 7.2 | 15 | 27 | |
| (-) | 0.02 | 39 | 72 | 51 | 19 | 38 | 19 | 33 | 52 | |

* = 0-3 GeV ** = 0-5 GeV, 1 MW. 10^7 s = 5.2×10^{20} POT at 120 GeV

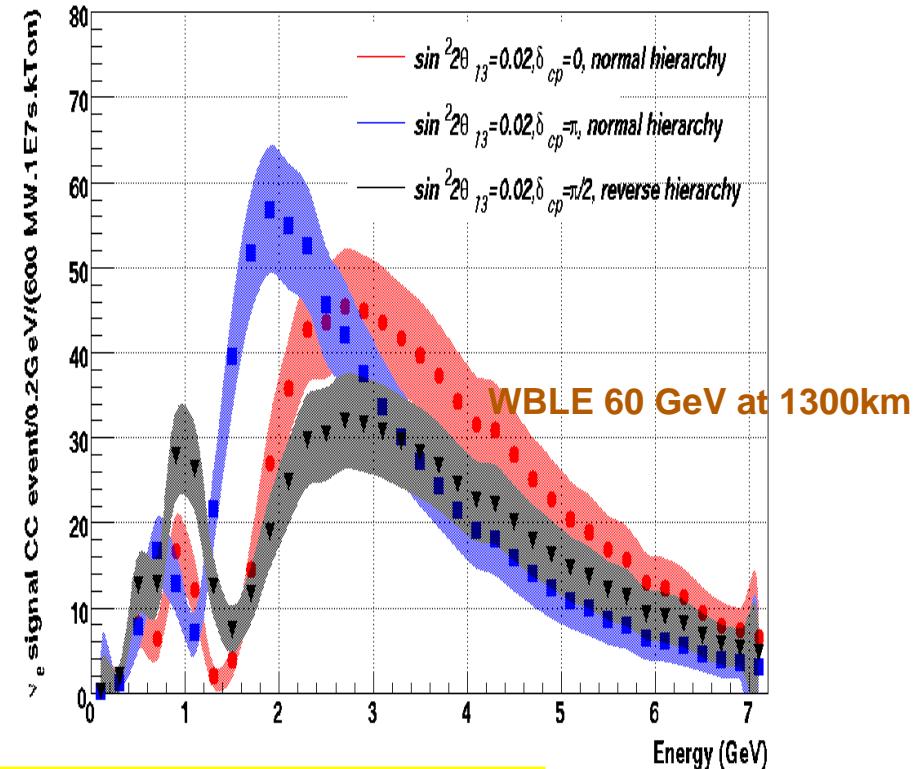
ν_e Appearance Spectra

- $\sin^2 2\theta_{13} = 0.02, \delta_{cp} = 0$, normal hierarchy
- $\sin^2 2\theta_{13} = 0.02, \delta_{cp} = \pi$, normal hierarchy
- $\sin^2 2\theta_{13} = 0.02, \delta_{cp} = -\pi/2$, reverse hierarchy

NuMI LE at 810 km, 15 mrad off-axis



WBLE 60 GeV at 1300km, 0° off-axis



Spectral information = resolves degeneracies

FAR DETECTOR DESIGN/SIMULATIONS

"Background Rejection Study in a water Cherenkov detector." C. Yanagisawa, C. K. Jung, P.T. Le, B. Viren, July 18, 2006

"T2KK Project & Likelihood study". Fanny Dufour, FNAL-BNL VLB workshop, September 16, 2006

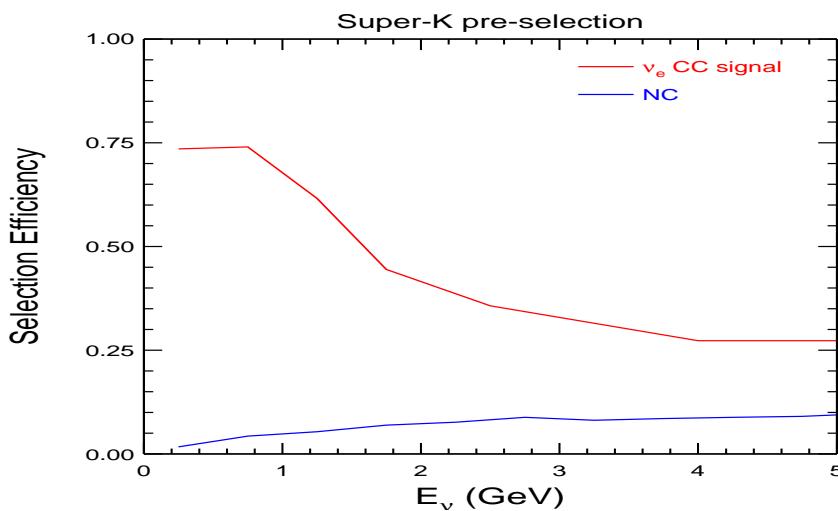
"Monte Carlo study of a liquid Ar time projection chamber for long baseline neutrino experiments." A. Curioni, August 10, 2006.

www-larptc.fnal.gov/LBStudy_LAr/2006LB.html

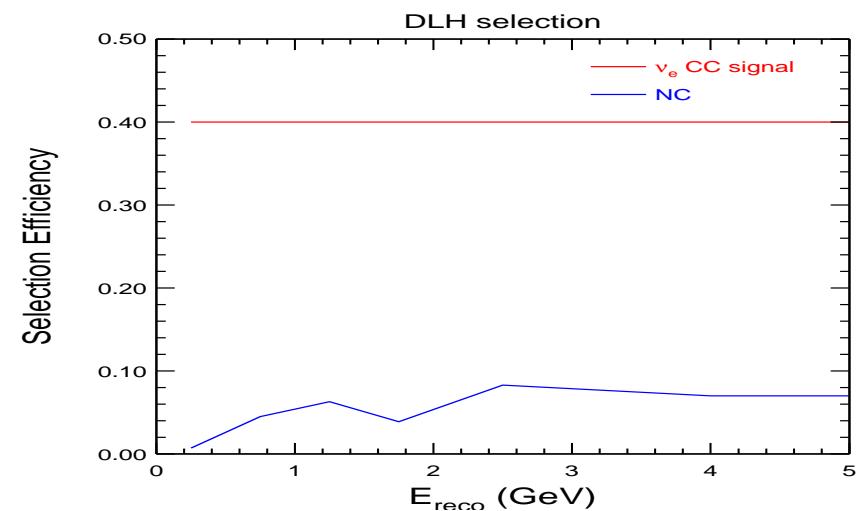
Water Cerenkov Simulation

The ν_{atm} GEANT simulation of SuperKamiokande is used.

An π^0 reconstruction algorithm called “Pattern Of Light Fit” is used as input to a likelihood (DLH) analysis to reconstruct $\pi^0 \rightarrow \gamma\gamma$ by looking for the 2nd ring. Independent studies by Chiaki Yanagisawa for FNAL-DUSEL WBB and Fanny Dufour for T2KK produce similar efficiency for signal and background.



Standard Super-K pre-selection efficiencies



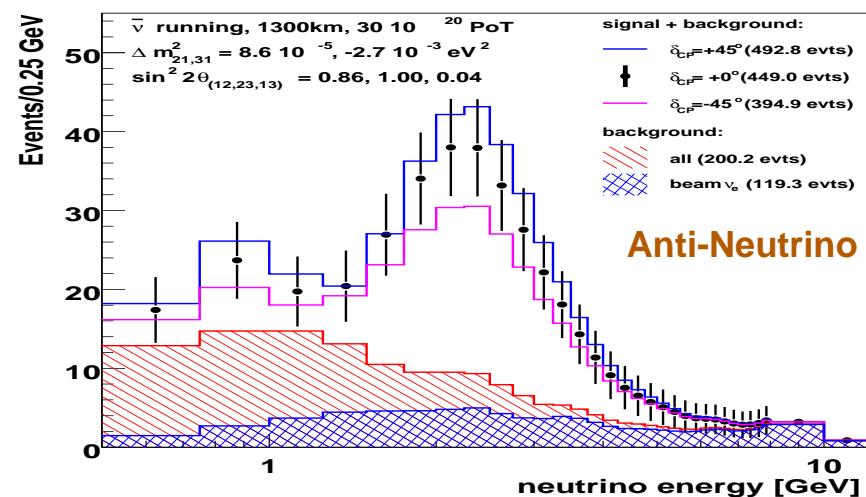
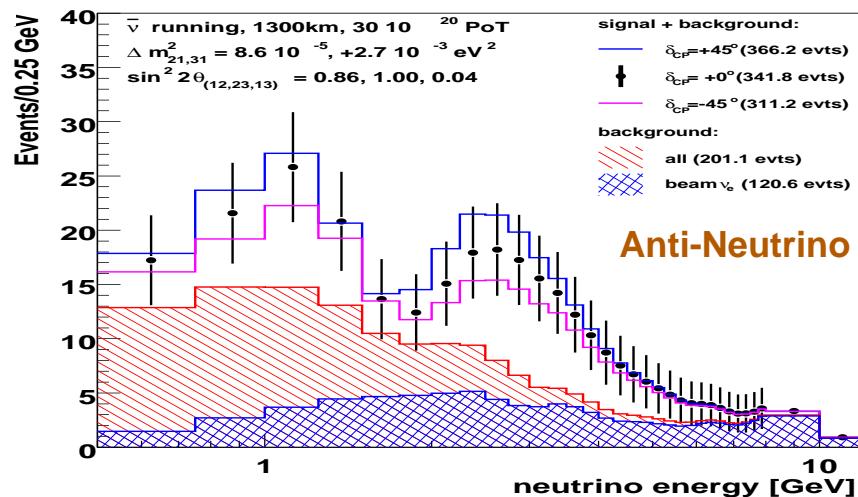
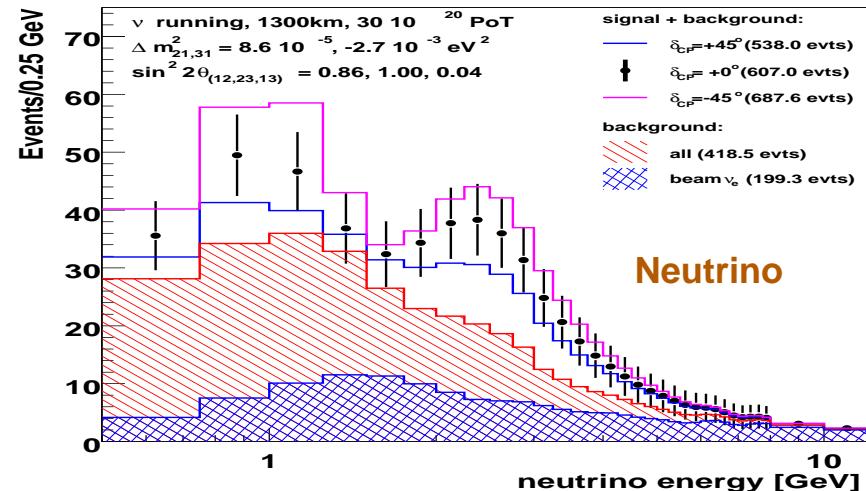
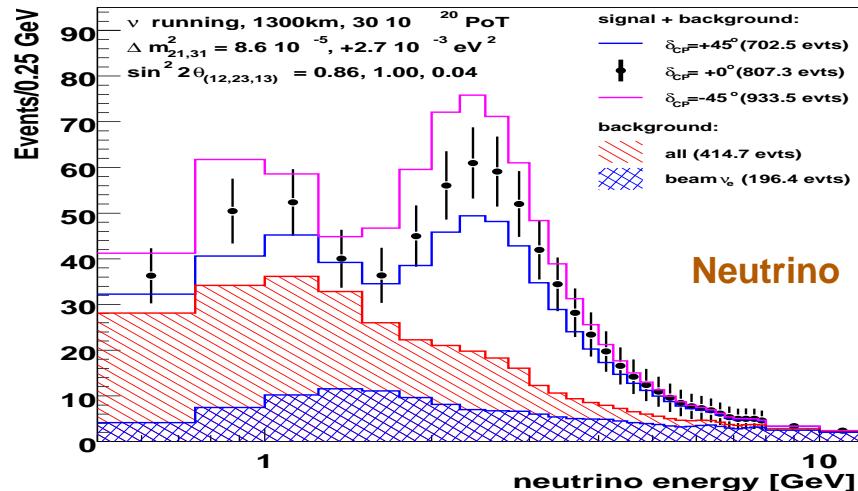
DLH selection efficiencies (Chiaki Y.)

WCe. energy dependent efficiencies and smearing implemented in GLoBeS.

GLoBeS ν_e Appearance Spectra

$\sin^2 2\theta_{13} = 0.04$, 300kT WCe., WBLE 120 GeV, 1300km, 30E20 POT.

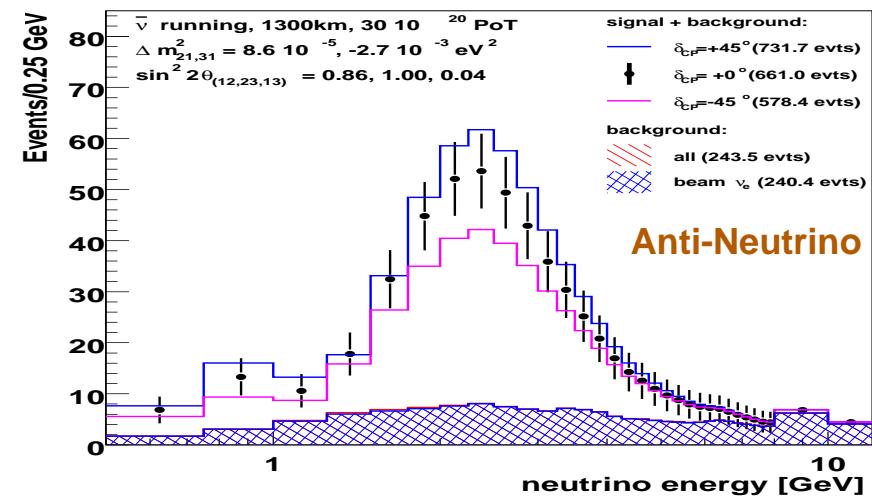
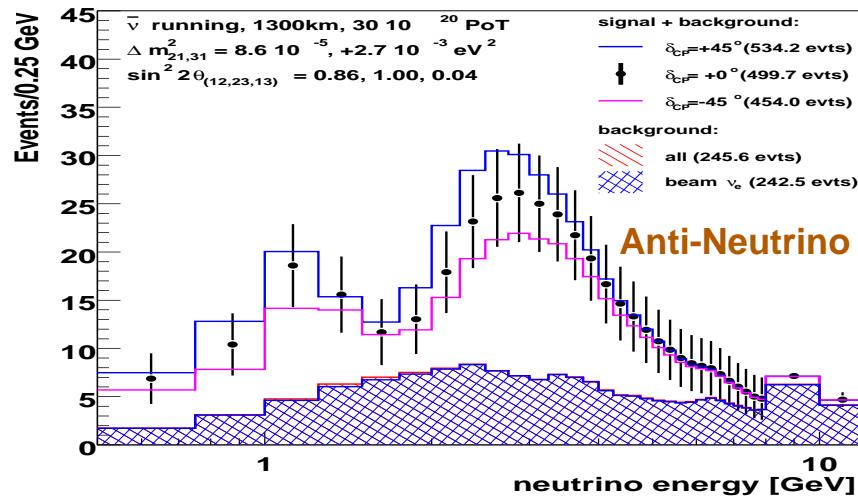
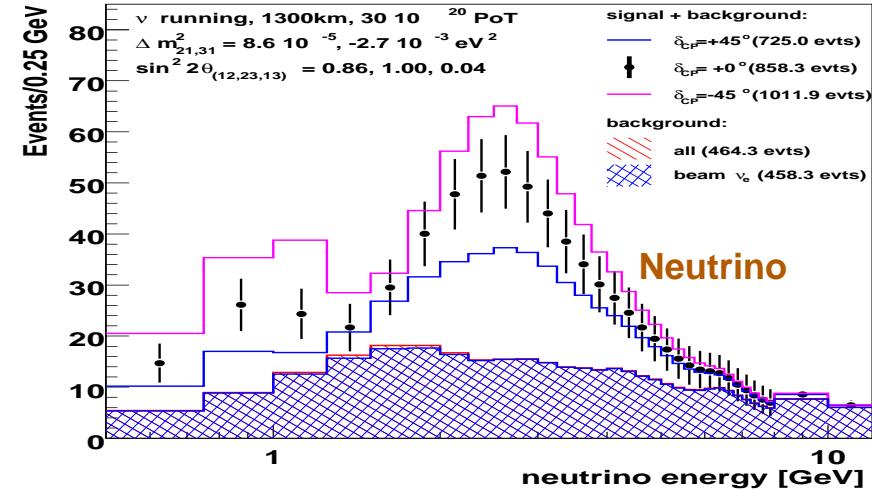
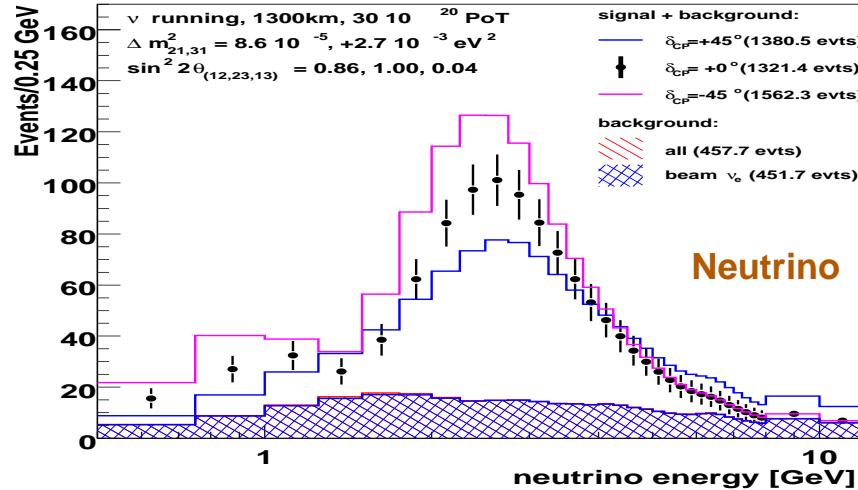
Normal hierarchy ($-\delta_{cp} = -45^\circ$, $-\delta_{cp} = +45^\circ$) Reversed hierarchy



GLoBeS ν_e Appearance Spectra

$\sin^2 2\theta_{13} = 0.04$, 100kT LAr., WBLE 120 GeV, 1300km, 30E20 POT.

Normal hierarchy ($-\delta_{cp} = -45^\circ$, $-\delta_{cp} = +45^\circ$) Reversed hierarchy



LAr simulation: 80% efficiency for ν_e CC, $\sigma(E)_{QE} = 5\% \cdot \sqrt{(E)}$, $\sigma(E)_{CC} = 20\% \cdot \sqrt{(E)}$

PHYSICS SENSITIVIES

V. Barger, M. Dierckxsens, M. Diwan, P. Huber, C. Lewis, D. Marfatia, B. Viren, Jul 17, 2006

hep-ph/0607177, BNL-76797-2006-JA

V. Barger, P. Huber, D. Marfatia and W. Winter Mar 4, 2007 hep-ph/0703029

Estimating sensitivities

Matrix parameters used & systematic uncertainties:

- $\Delta m_{21,31}^2 = 8.6 \times 10^{-5}$ (5%), 2.7×10^{-3} eV² (uncertainty determined from fit to disappearance mode) - $\sin^2 2\theta_{12,23} = 0.86$ (5%), 1.0(uncertainty determined from fit to disappearance mode) -Matter density (5%) -Background (10%)

Determining θ_{13} sensitivity: Fit the appearance spectrum generated for various values of θ_{13} and δ_{cp} to the oscillation hypothesis with θ_{13} set to 0.0. Mass hierarchy is fixed.

CP-violation sensitivity: Fit the appearance spectrum to the oscillation hypothesis with $\delta_{cp} = 0$ and π . Take the worst χ^2 .

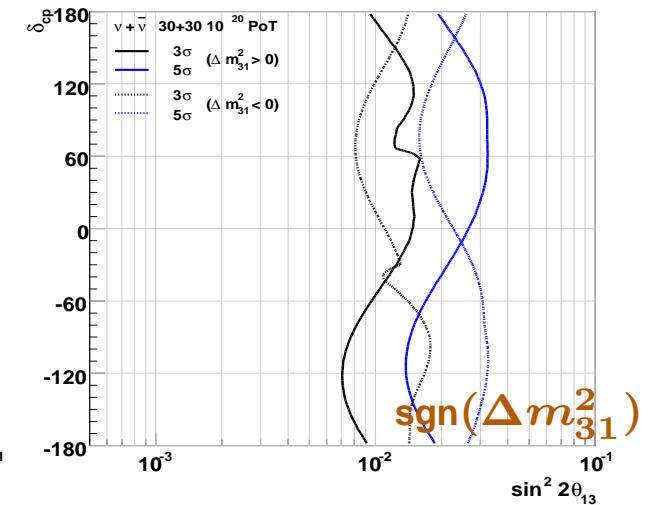
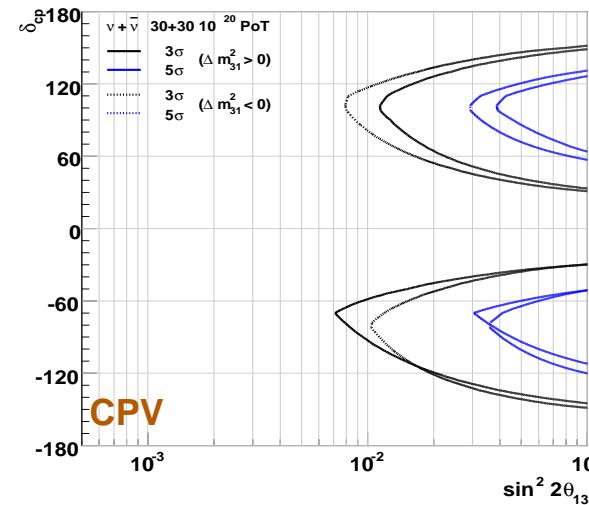
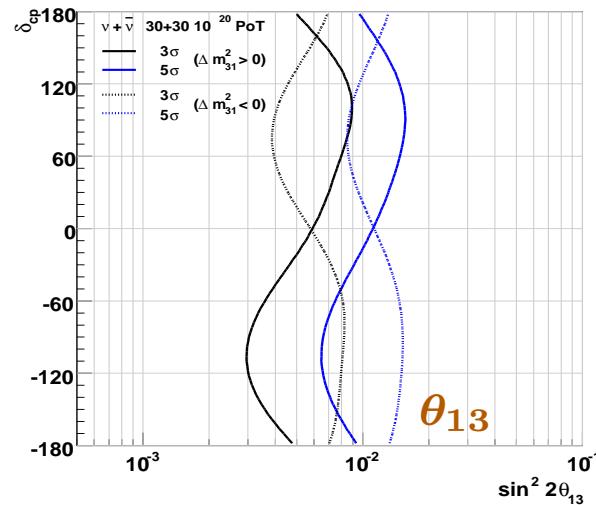
θ_{13} is allowed to float in the fit. Mass hierarchy is fixed.

$\text{sign}(\Delta m_{31}^2)$: Fit the appearance spectrum to the oscillation hypothesis with the opposite mass hierarchy.

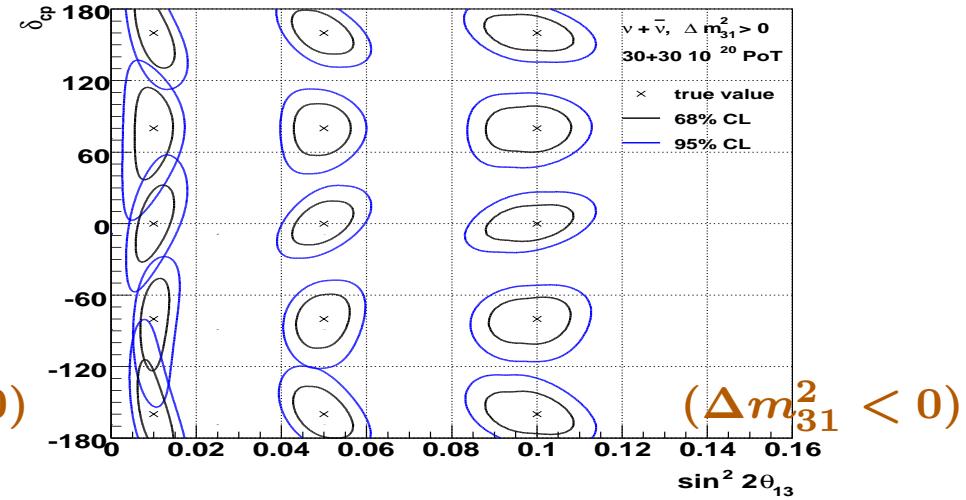
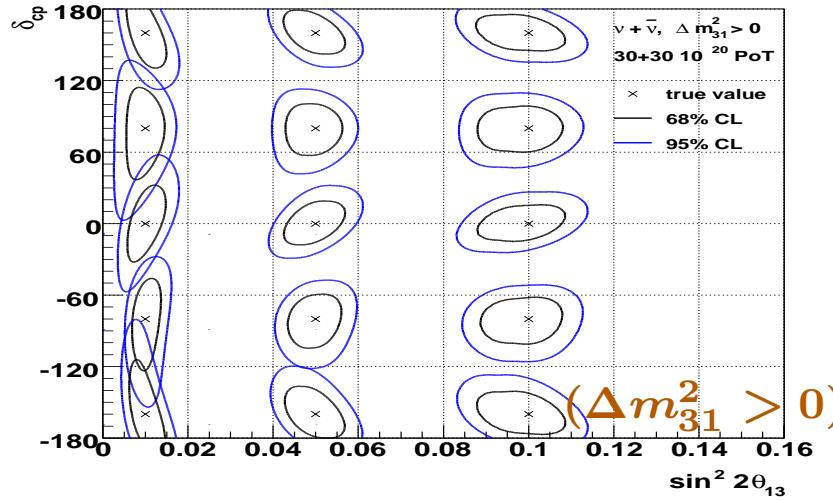
BOTH θ_{13} and δ_{cp} are allowed to float in the fit.

WBLE to DUSEL (1300km)

Discovery potential (-5σ – 3σ). WCe. 300 kT , 1.2 MW, 6yrs:

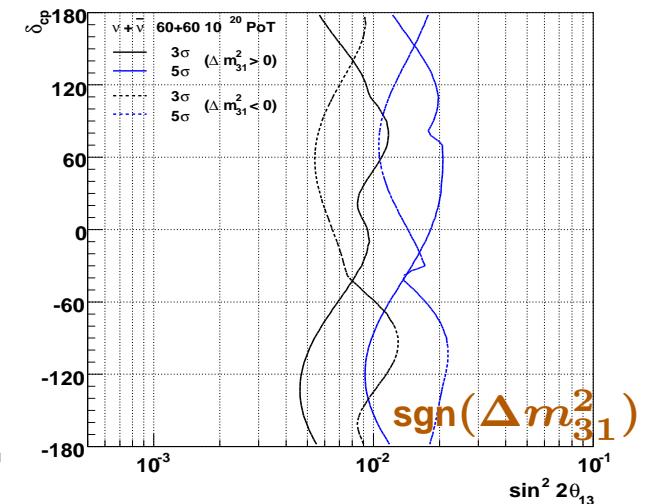
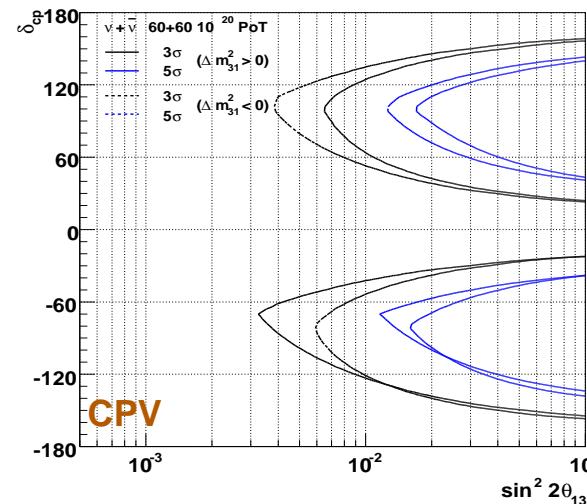
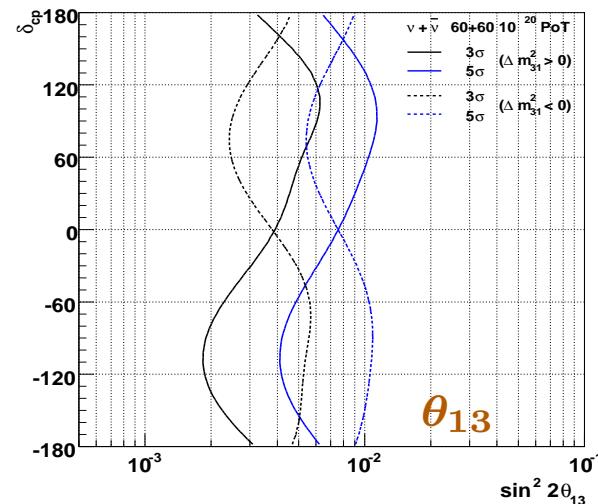


Measurement ($-95\% \text{ CL}$ – $-68\% \text{ CL}$):

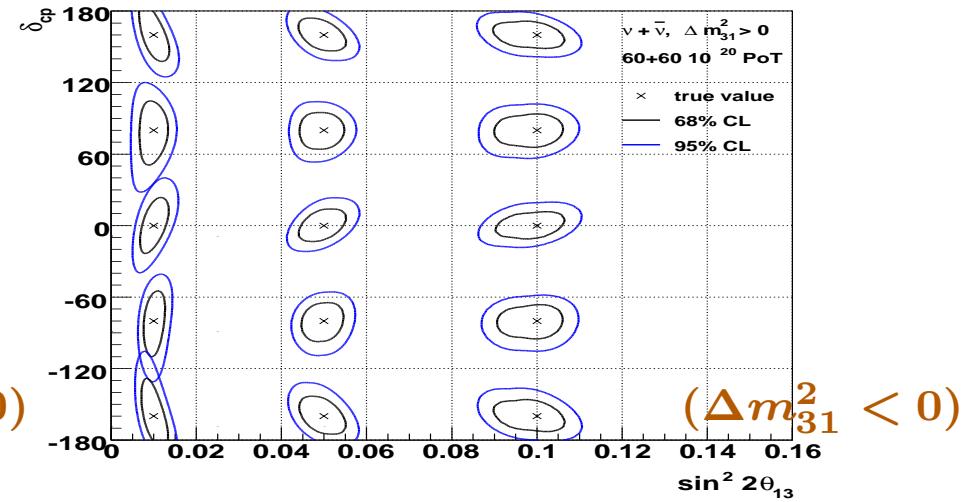
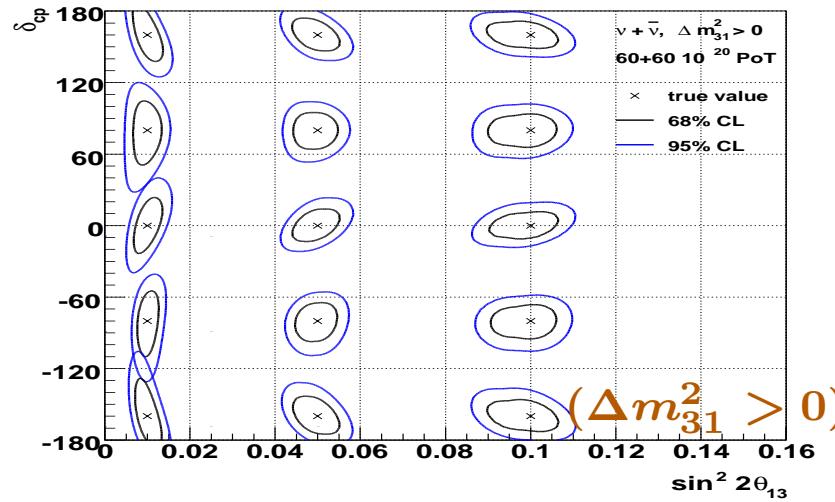


WBLE to DUSEL (1300km)

Discovery potential (-5σ -3σ). WCe. 300 kT, 1.2 (2) MW, 12 (7) yrs:

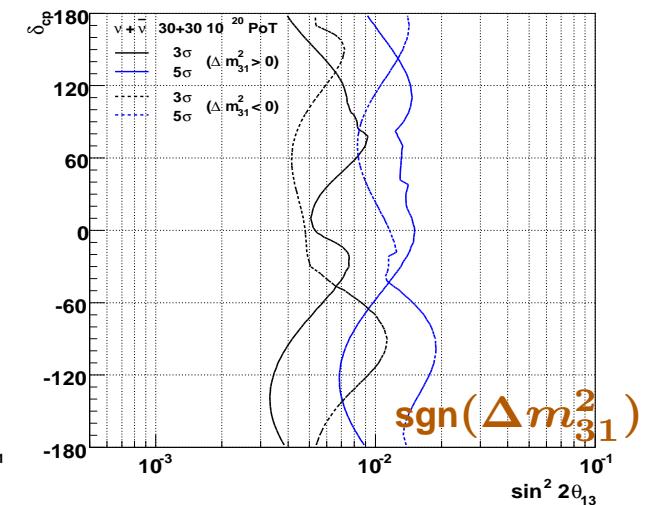
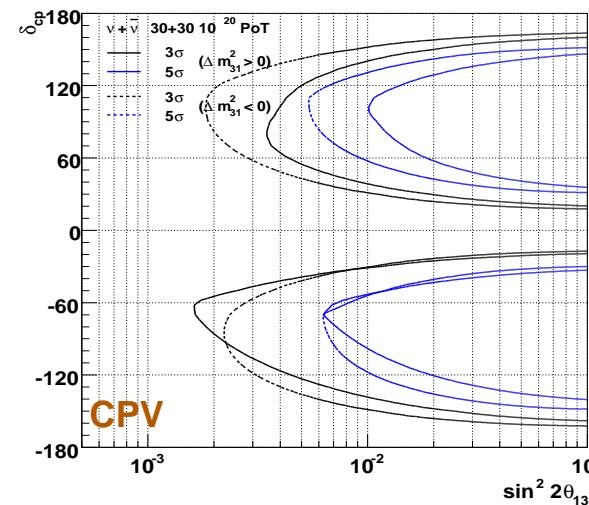
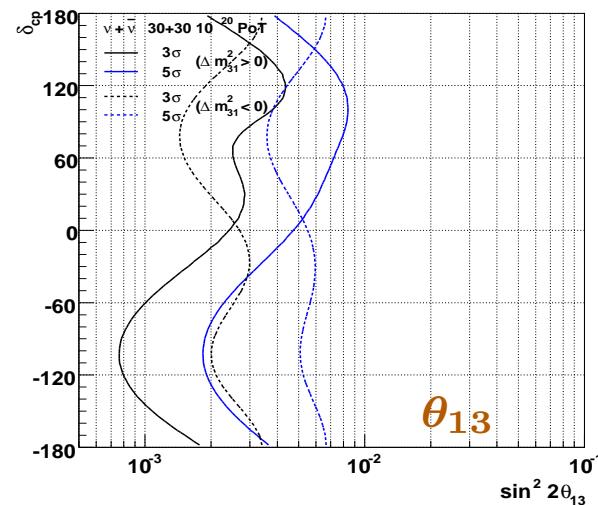


Measurement ($-95\% \text{ CL}$ $-68\% \text{ CL}$):

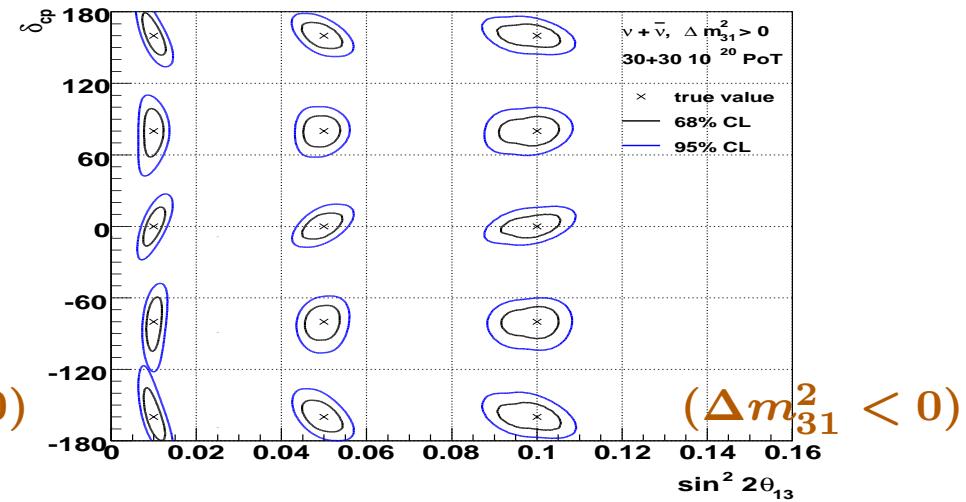
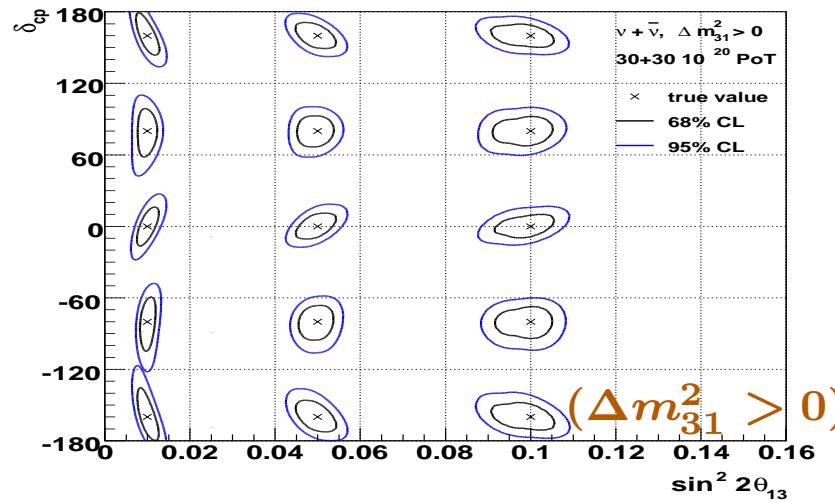


WBLE to DUSEL (1300km)

Discovery potential (-5σ -3σ). LAr. 100 kT, 1.2 MW, 6yrs:



Measurement ($-95\% \text{ CL}$ $-68\% \text{ CL}$):



Milestones

- Detailed study of different FNAL beam power scenarios
- Conceptual design of beamline to DUSEL from FNAL
- Detailed definition/simulation of a WBLE beam from FNAL complete.
- Detailed simulation of ν_e signal and backgrounds in a Water Cerenkov detector complete.
- MC for LAr under development. Performance is based on eye scanning with a narrow band beam.
- Physics sensitivities using a FNAL based WBLE beam to DUSEL with a 300kT WC and 100 kT LArTPC computed.
- Preliminary cost, timelines for building a modularized 300 kT Water Cerenkov detector at Homestake Mine produced (for discussion).

First draft of the study report is in preparation.

FOR FURTHER DISCUSSION

NUSAG Charge

**Address APS Study's recommendation for a next generation neutrino beam
and detector configurations**



*U.S. Department of Energy
and the
National Science Foundation*



March 3, 2006

Professor Eugene Beier
Co-Chair, NuSAG
University of Pennsylvania
209 South 33rd Street
Philadelphia, PA 19104

Professor Peter Meyers
Co-Chair, NuSAG
Princeton University
306 Jadwin Hall
Princeton, NJ 08544

Dear Professors Beier and Meyers:

We would like to thank you and the Neutrino Scientific Assessment Group (NuSAG) for your timely and thoughtful responses to the initial questions that were posed to you, concerning neutrinoless double beta decay, reactor experiments and accelerator-based experiments to determine fundamental neutrino properties. They have already been very useful and will help us put together a strong US program in neutrino physics.

We would now like your group to address the APS Study's recommendation for a next-generation neutrino beam and detector configurations. Assuming a megawatt class proton accelerator as a neutrino source, please answer the following questions for accelerator-detector configurations including those needed for a multi-phase off-axis program and a very-long-baseline broad-band program. This assessment will be used as one of the key elements to guide the direction and timeline of such a possible next generation neutrino beam facility.

In your assessment, NuSAG should look at the scientific potential of the facility, the timeliness of its scientific output, and its place in the broad international context. Specifically:

- **Scientific potential:** What are the important physics questions that can be addressed at the envisioned neutrino beam facility?
- **Associated detector options:** What are the associated detector options which might be needed to fully realize the envisioned physics potentials? What are the rough cost ranges for these detector options?
- **Optimal timeline:** What would be the optimal construction and operation timeline for each accelerator-detector configuration, taking the international context into account?
- **Other scientific considerations:** What other scientific considerations, such as results from other neutrino experiments, will be important in order to optimally determine the design parameters? What would be additional important physics questions that can be addressed in the same detector(s)?

The DOE and the NSF would like a preliminary draft of your report by December 2006, with a final version by February 2007.

- **What are the physics questions to be addressed?**
- **What are the detector options needed to realize the physics? Rough Costs?**
- **What is the optimal construction and operation timeline?**
- **What would be additional important physics questions that can be addressed by the same detector?**

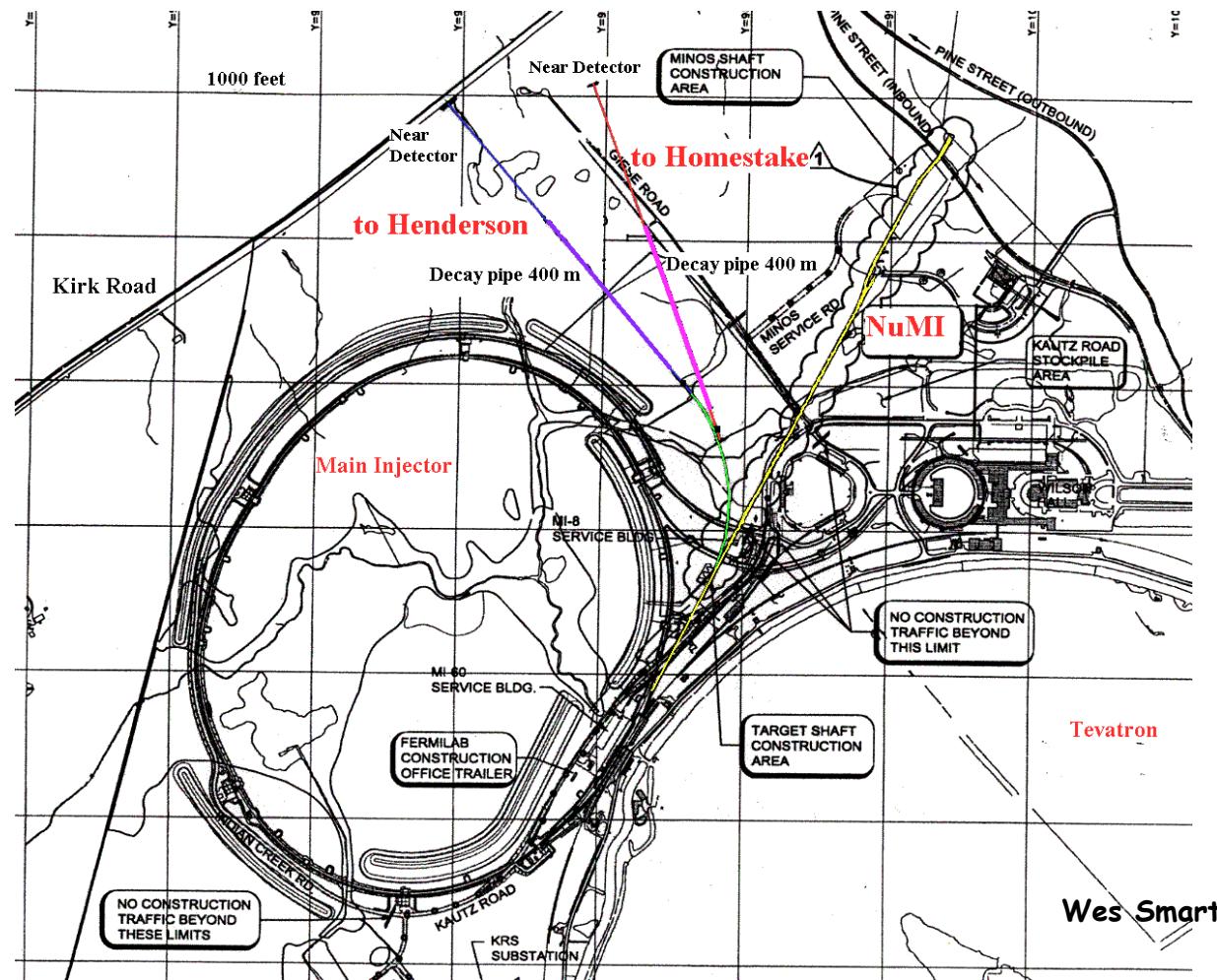
BEAMLINE DESIGN/SIMULATIONS

"Target System for a Long Baseline Neutrino Beam," N. Simos, H. Kirk, J. Gallardo, S. Kahn, N. Mokhov.
June 26, 2006.

"Simulation of a Wide-band Low-Energy Neutrino Beam for Very Long Baseline Neutrino Oscillation
Experiments," M. Bishai, J. Heim, C. Lewis, A. D. Marino, B. Viren, F. Yumiceva, July 20, 2006

DUSEL Beamlne Siting at FNAL

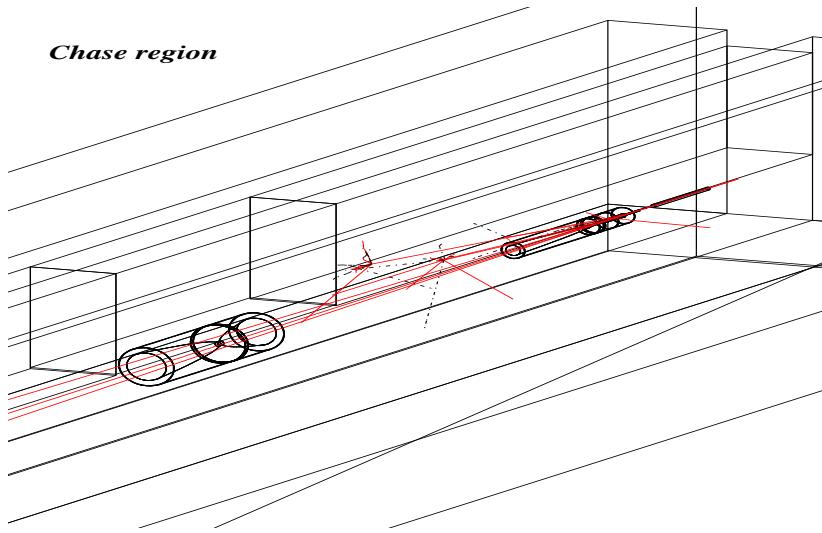
Greg Bock, Dixon Bogert, Wes Smart (FNAL)



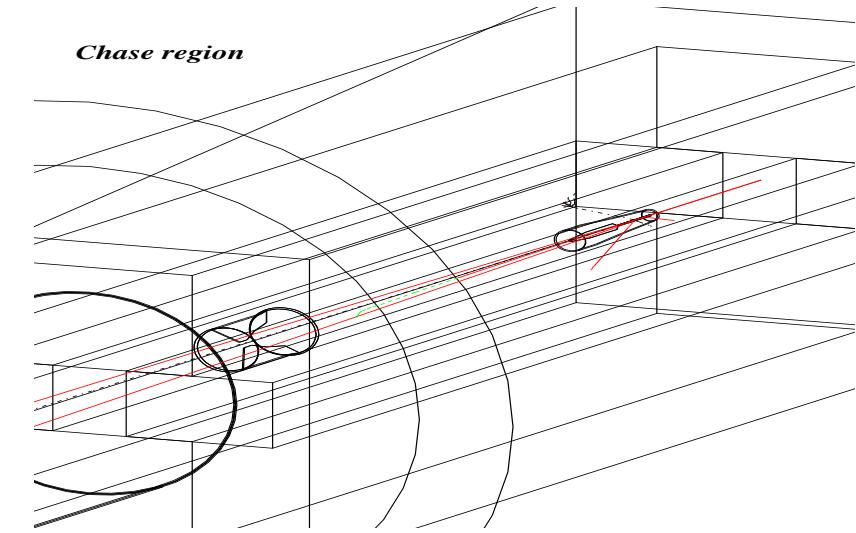
Beamlines to DUSEL can accomodate a decay tunnel with $L \leq 400\text{m}$ on-site

NuMI/WBLE simulation

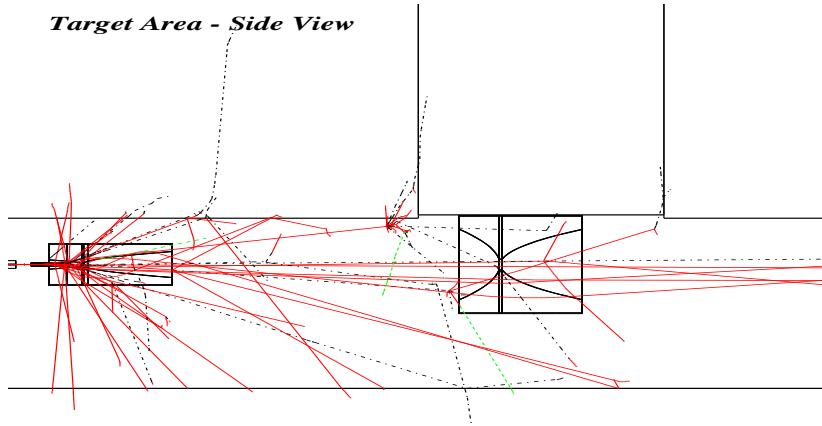
NuMI horns/target with 120 GeV p+



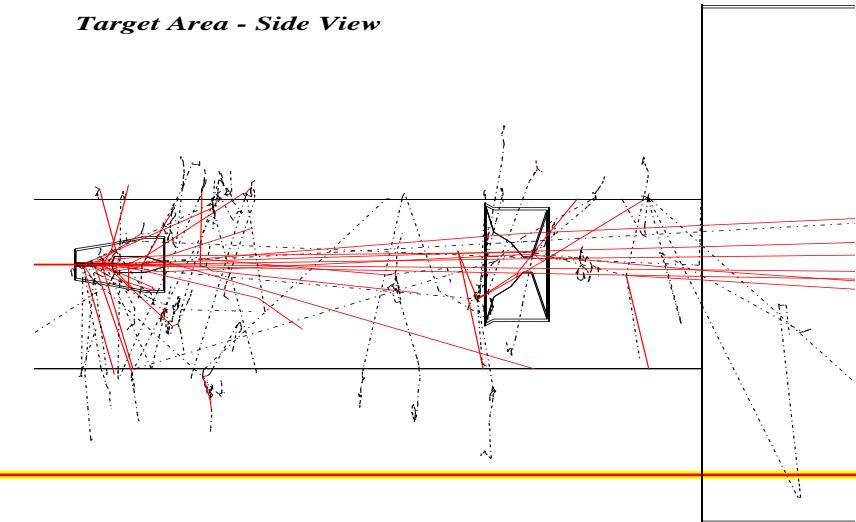
WBLE horns/target with 120 GeV p+



Target Area - Side View



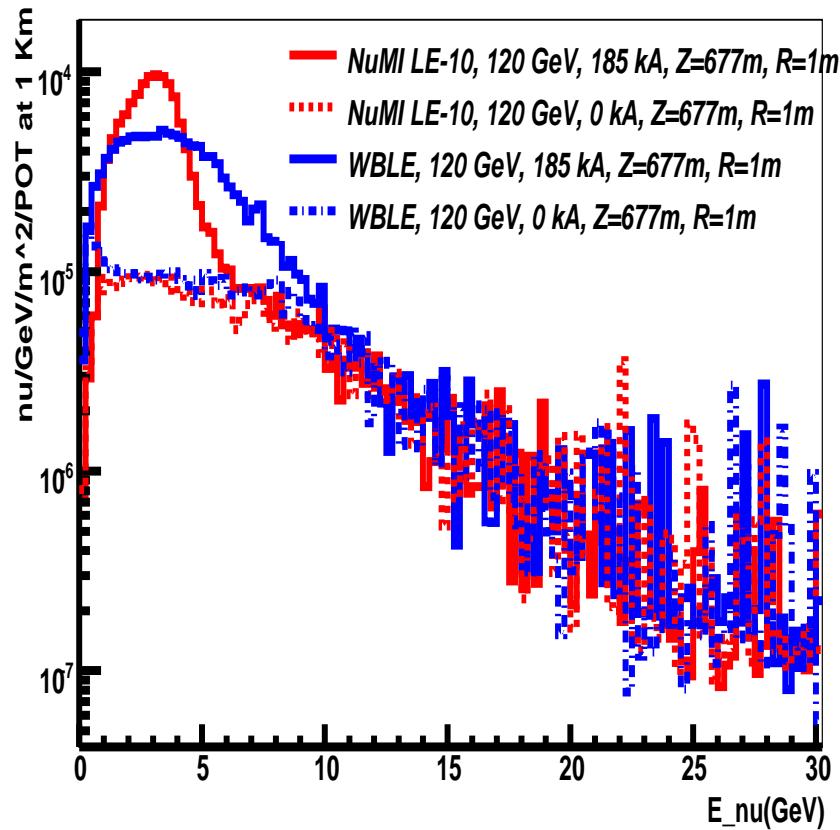
Target Area - Side View



NuMI LE vs WBLE

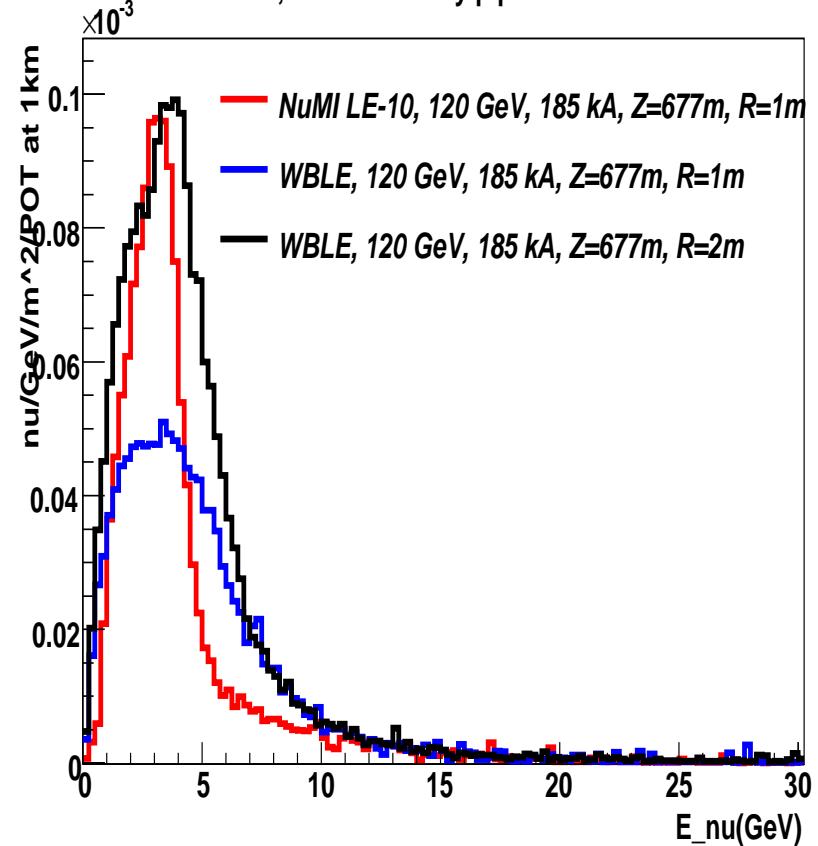
R and Z refer to the geometry of the decay volume which is cylindrical.

NuMI LE-10 vs WBLE spectra



1m radius decay pipe

NuMI LE-10 vs WBLE, increase decay pipe radius



increase to 2m radius

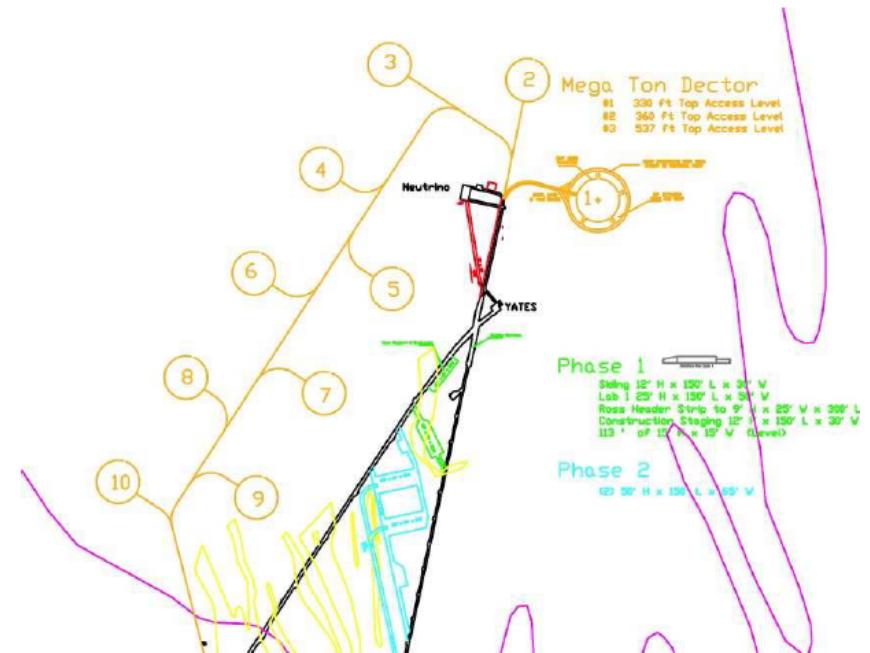
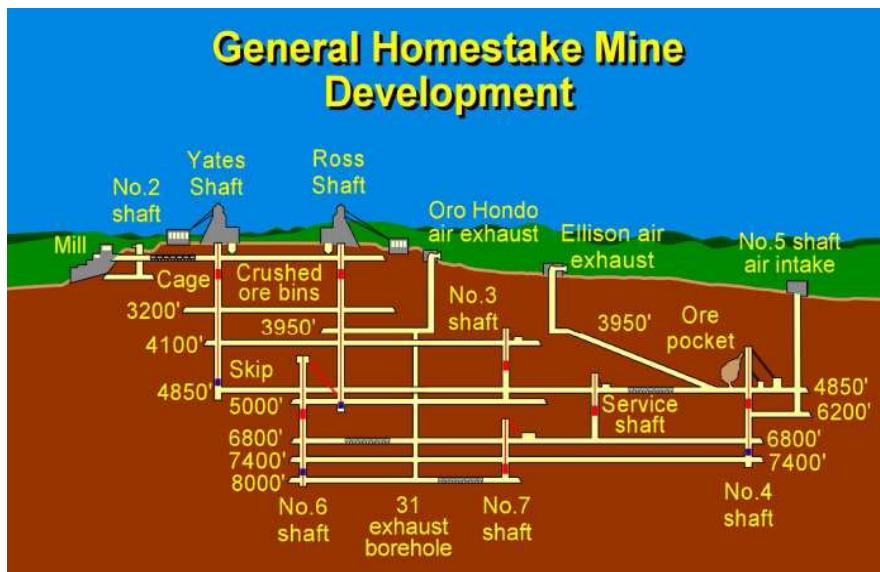
Larger diameter decay pipe = more flux at low E.

FAR SITE PRELIMINARY DESIGN,COST,SCHEDULE (Homestake Mine)

"Proposal for an Experimental Program in Neutrino Physics and Proton Decay in the Homestake Laboratory," Collaboration: BNL, Brown University, UC/Berkeley, LBNL, University of Pennsylvania, Princeton University, UCLA, University of Wisconsin, University of Kansas, University of Colorado. July 12, 2006. BNL-76798-2006-IR

"Large Cavity Excavation". William Pariseau (University of Utah), FNAL-BNL VLB workshop, September 16, 2006

Modularized Detectors at HS

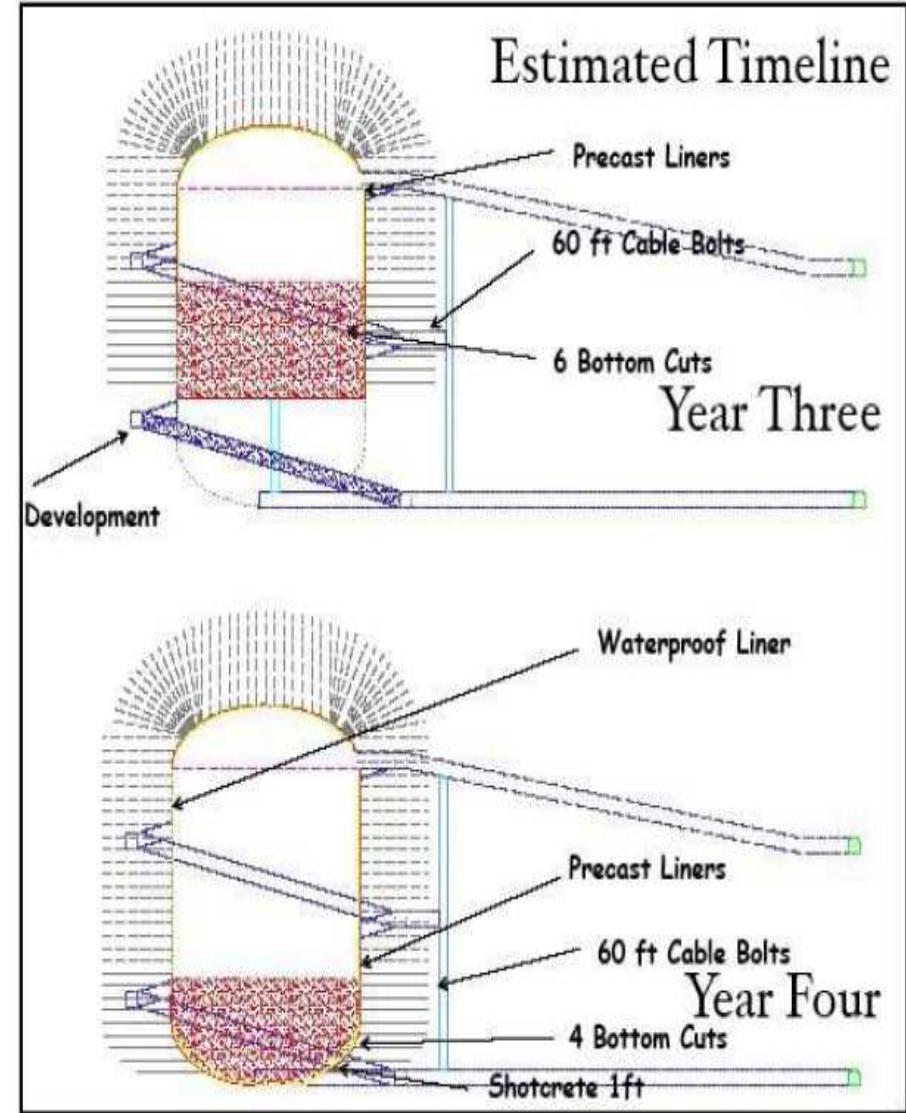
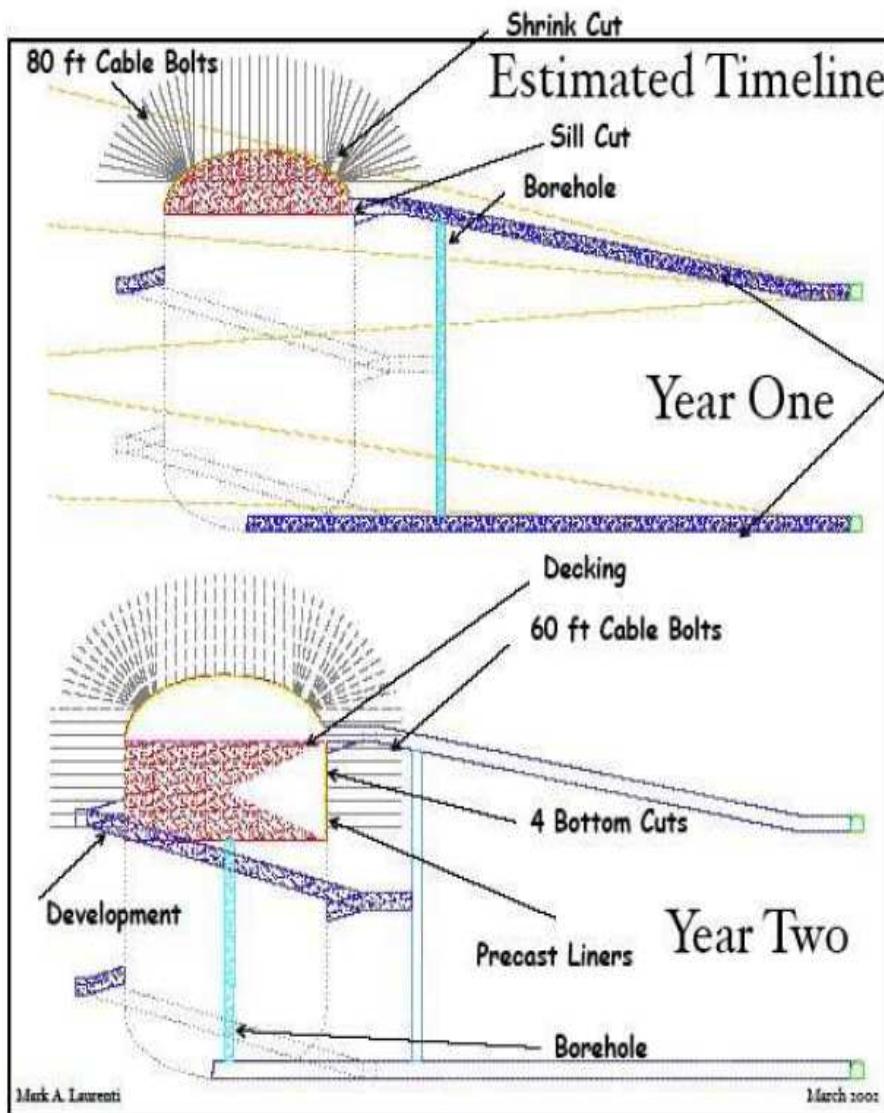


The detector system will be deployed in the 4850 ft level as separate 100kT Water Cerenkov detector modules to allow a staged approach with potential for expansion.

The first modules will be located near the original cavern for the Ray Davis experiment.

Cavern Construction Timeline

Mark Laurenti, Chief Mine Engineer for Homestake till 2001



Cost Estimates for 300 kT (fiducial)

Construction costs for 3 caverns:

| Cost Description | Amount |
|---------------------------------|---------|
| Labor/benefits | \$19.3M |
| Minig equipment | \$5.30M |
| Mining equipment operations | \$4.55M |
| Supplies | \$15.8M |
| precast concrete liner | \$11.4M |
| Plastic liner | \$0.79M |
| Outside contractor (bore holes) | \$0.42M |
| Rock removal | \$3.18M |
| Contingency | \$18.2 |
| Total for 3 chambers | \$78.9 |

Detector costs

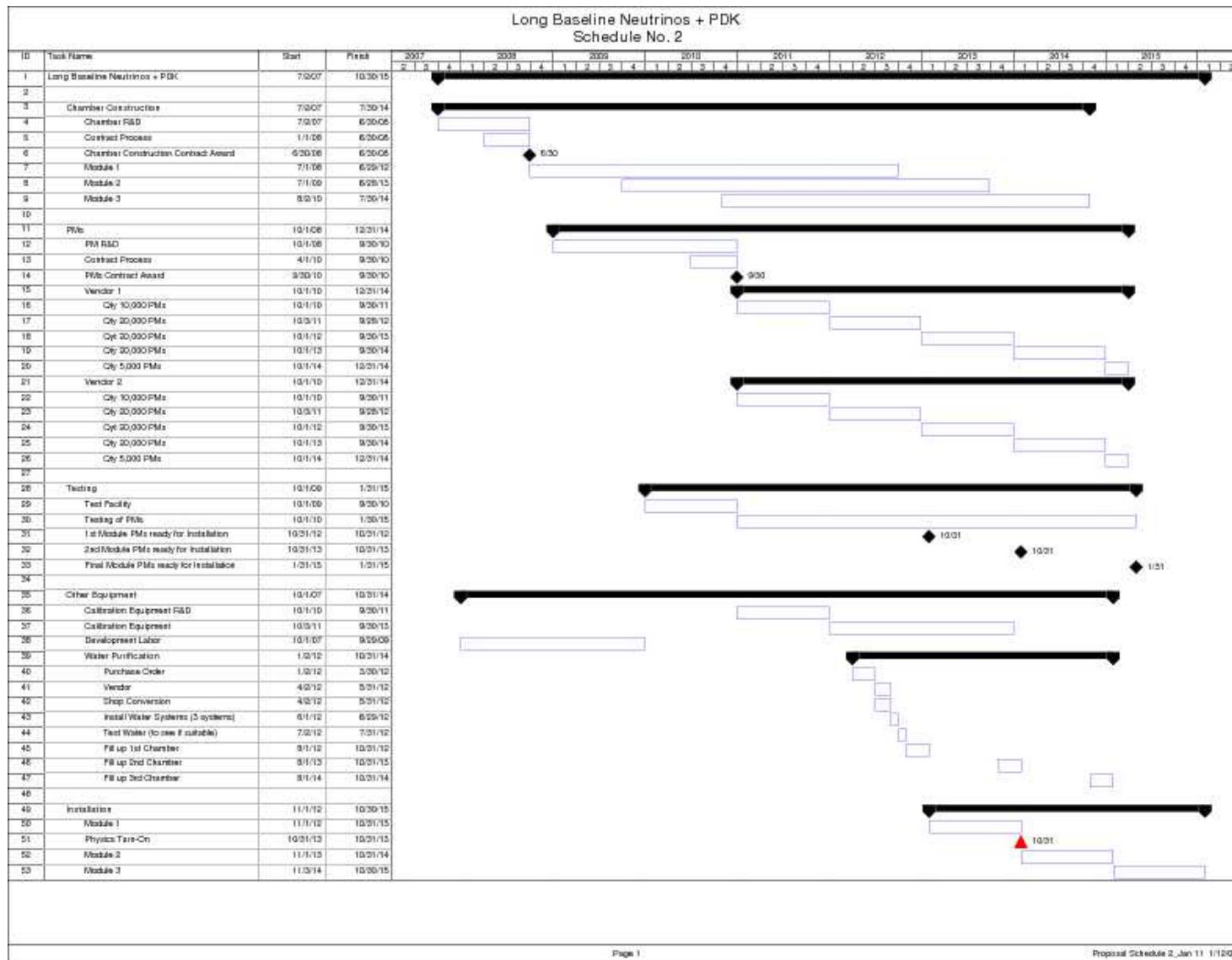
For 25% PMT coverage of 11,000m² using 8" PMTs. Extrapolated from SNO.

| Cost Description | Amount |
|---------------------------------|----------|
| PMT+electronics | \$171.3M |
| R&D,Water,DAQ, etc | \$8.2M |
| Installation+testing | \$35.7M |
| Contingency (non-civil) | \$50.8M |
| Total detector cost (3 Modules) | \$266.0M |

Total cost for 300kT (2007) : \$345M

Costs DO NOT include management overheads.

Overall Timeline



PHYSICS SENSITIVIES

" V. Barger, M. Dierckxsens, M. Diwan, P. Huber, C. Lewis, D. Marfatia, B. Viren, Jul 17, 2006 hep-ph/0607177

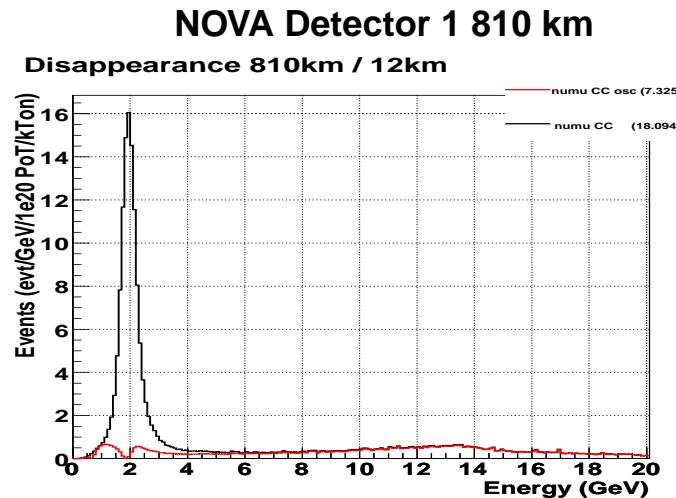
for a local copy BNL-76797-2006-JA

ν_μ Disappearance Rates

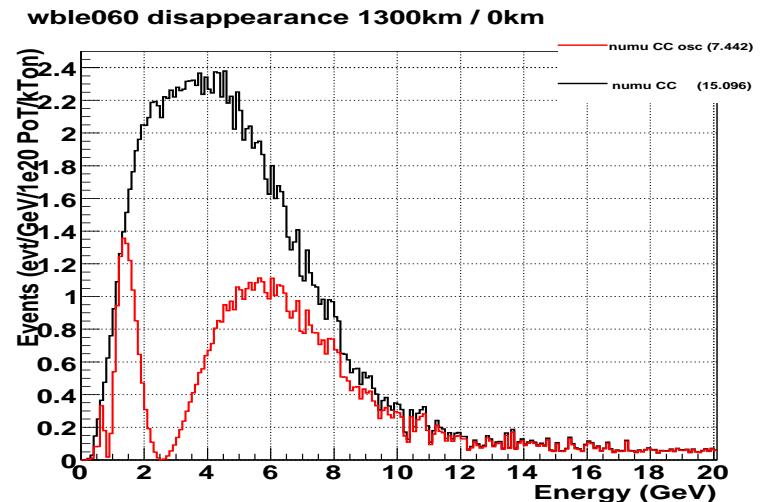
NO DETECTOR MODEL.

$-\nu_\mu$ CC no osc.

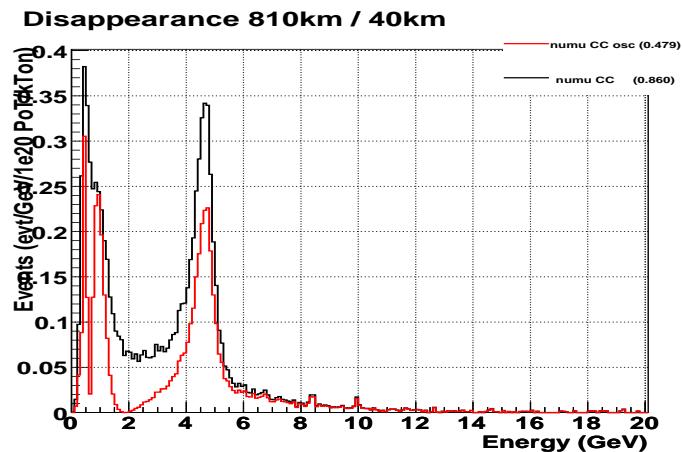
$-\nu_\mu$ CC with osc.



WBLE 60 GeV, 1300 km on-axis



NOVA Detector 2 810 km

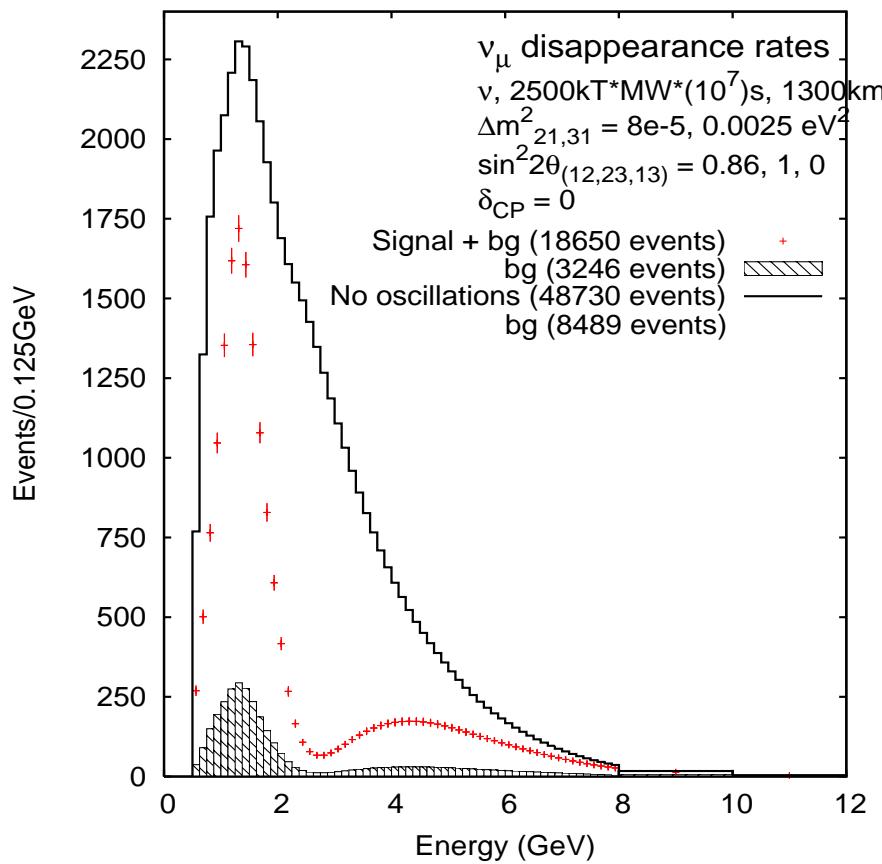


WBLE ν_μ Disappearance Spectra

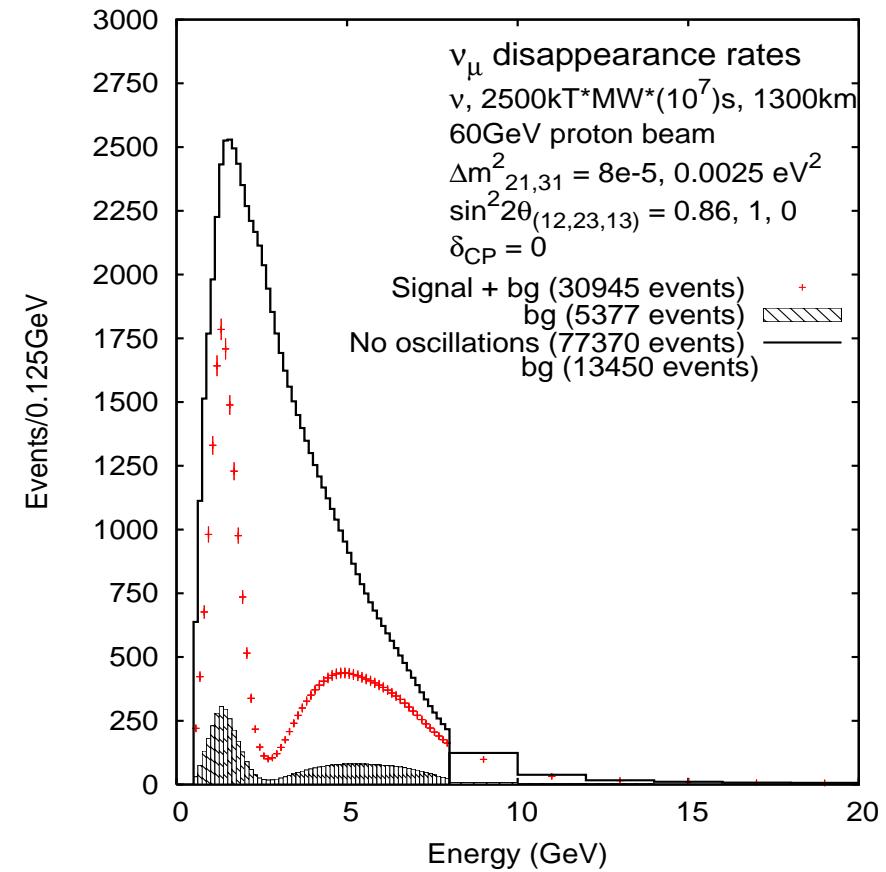
Parameterized WCe. Model in GLoBES.

1300km at 2500 MW.kT. 10^7 s.

WBB 28 GeV



WBLE 60 GeV

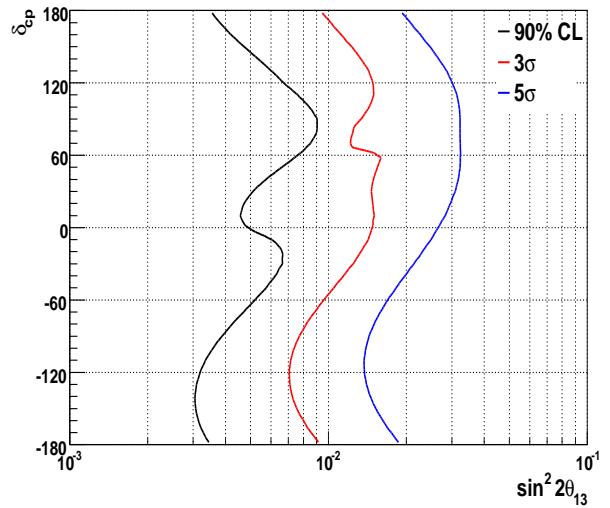
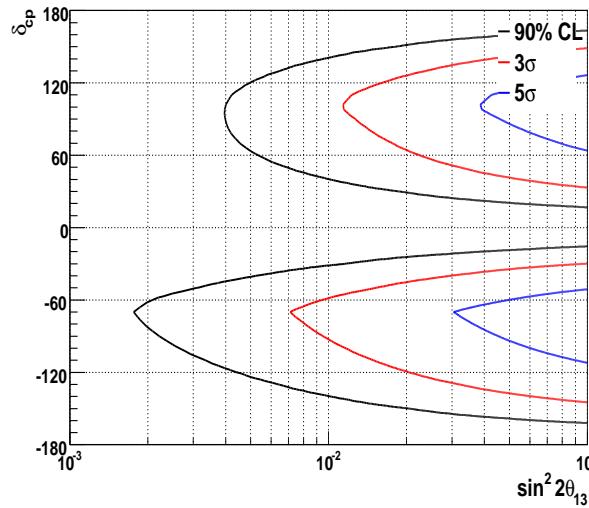
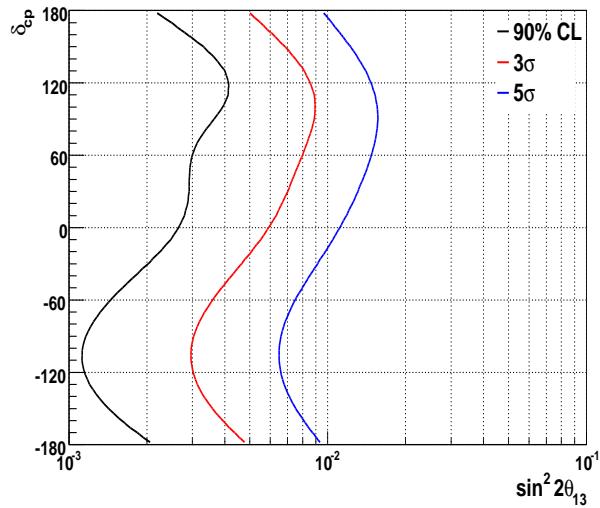


WCe. Background Composition

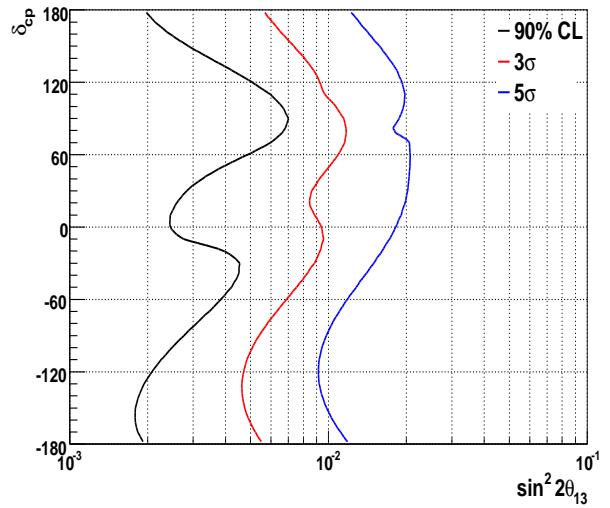
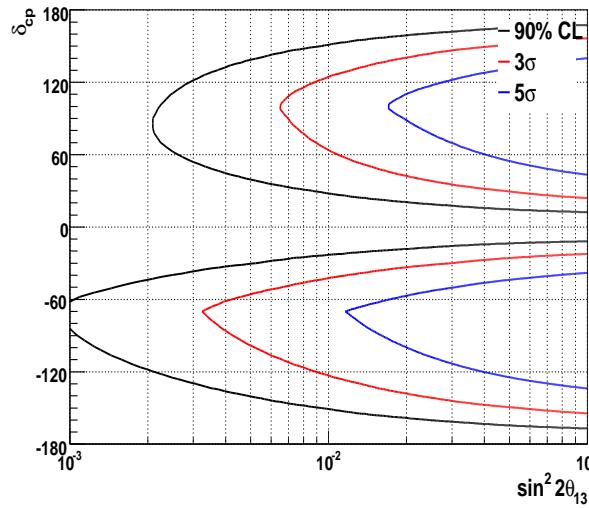
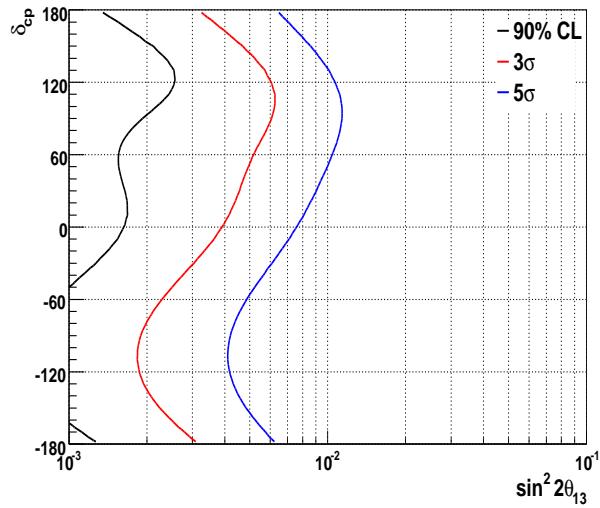
| Interaction | E_{rec} range (GeV) | | | | | |
|--------------|-----------------------|---------|---------|---------|---------|------|
| | 0.0-0.5 | 0.5-1.0 | 1.0-1.5 | 1.5-2.0 | 2.0-3.0 | 3.0- |
| Sig | 0.0-0.5 | 0.5-1.0 | 1.0-1.5 | 1.5-2.0 | 2.0-3.0 | 3.0- |
| CC QE | 80% | 78% | 36% | 53% | 58% | 55% |
| CC π^0 | 3% | 3% | 9% | 5% | 4% | 5% |
| CC π^\pm | 15% | 15% | 39% | 30% | 27% | 27% |
| CC $n\pi$ | 1% | 3% | 14% | 10% | 9% | 10% |
| CC others | 0% | 2% | 4% | 2% | 5% | 4% |
| Bkg 1 | 0.0-0.5 | 0.5-1.0 | 1.0-1.5 | 1.5-2.0 | 2.0-3.0 | 3.0- |
| CC QE | 7% | 4% | 1% | 3% | 0% | 0% |
| CC π^0 | 0% | 2% | 6% | 4% | 0% | 0% |
| CC π^\pm | 5% | 5% | 0% | 1% | 1% | 0% |
| CC $n\pi$ | 0% | 0% | 1% | 6% | 7% | 1% |
| CC others | 0% | 0% | 2% | 0% | 0% | 0% |
| NC π^0 | 20% | 54% | 62% | 50% | 26% | 0% |
| NC π^\pm | 53% | 9% | 6% | 0% | 0% | 0% |
| NC $n\pi$ | 0% | 13% | 5% | 21% | 62% | 99% |
| NC others | 15% | 14% | 16% | 21% | 1% | 0% |

WBLE to DUSEL (1300km) + WCe

ν 30×10^{20} POT+ same for $\bar{\nu}$. WCe. 300 kT, 1.2 MW, 6yrs, normal.:

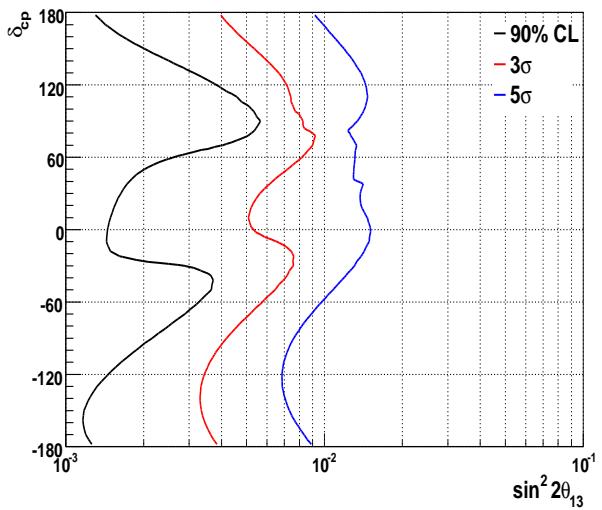
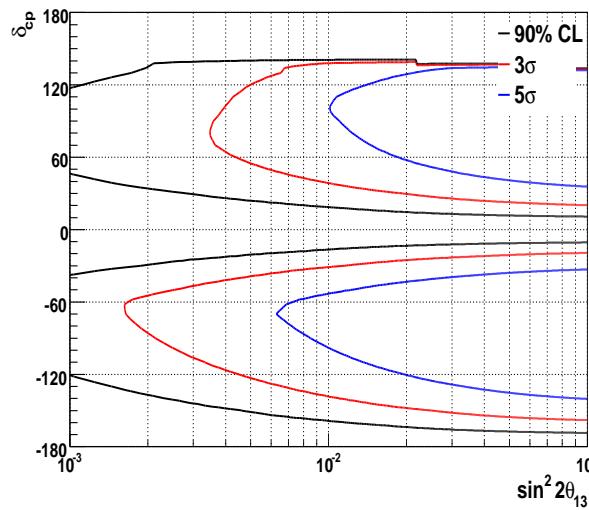
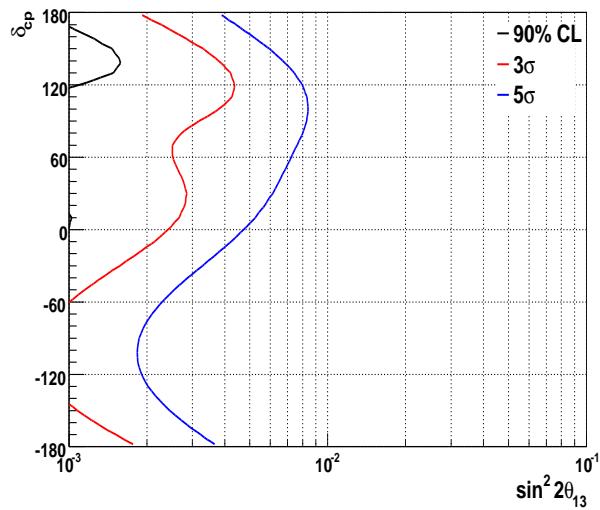


ν 60×10^{20} POT+ same for $\bar{\nu}$. WCe. 300 kT, 1.2 (2) MW, 12 (7) yrs, normal:



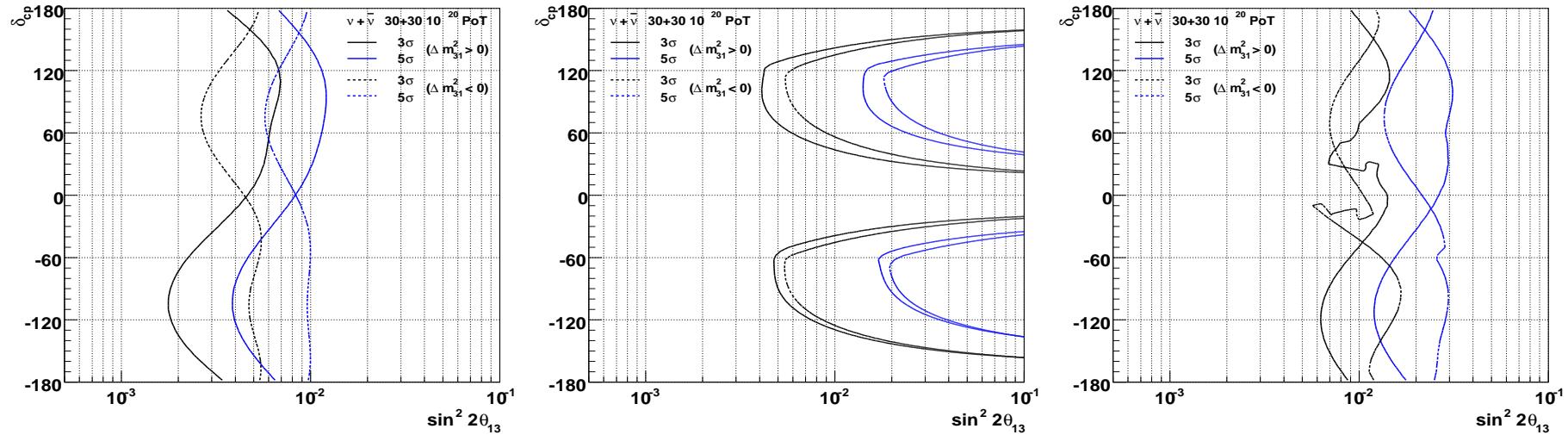
WBLE to DUSEL (1300km) + LAr

ν 30×10^{20} POT+ same for $\bar{\nu}$. LAr 100 kT, 1.2 MW beam, 6yrs, normal:



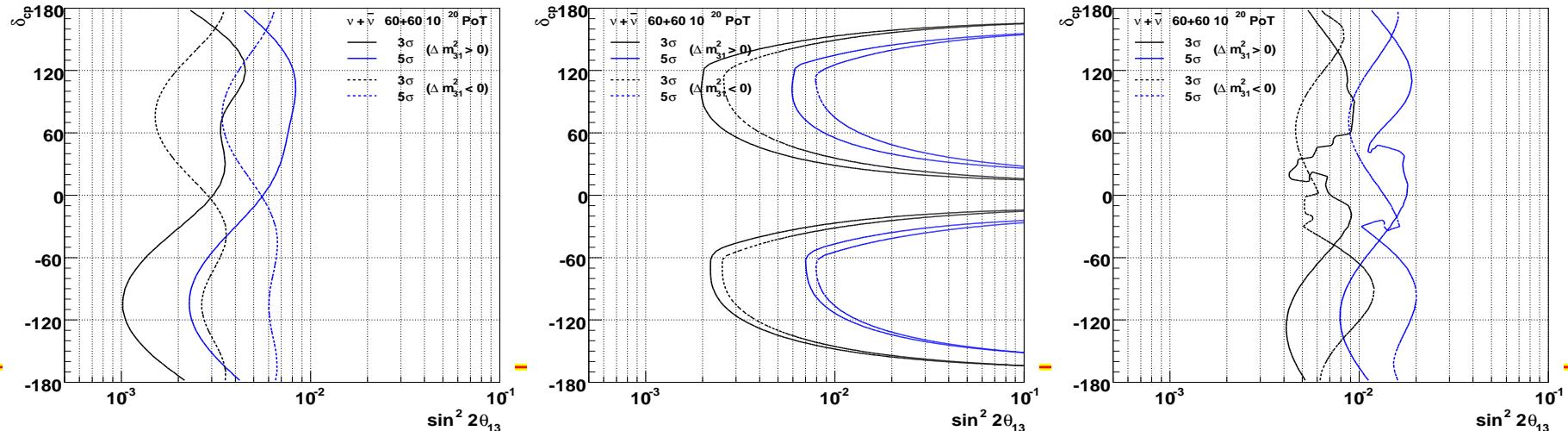
WBLE to DUSEL (1300km) + WCe

ν 30×10^{20} POT+ same for $\bar{\nu}$. WCe. 300 kT, 1.2 MW, 6yrs, stat only:



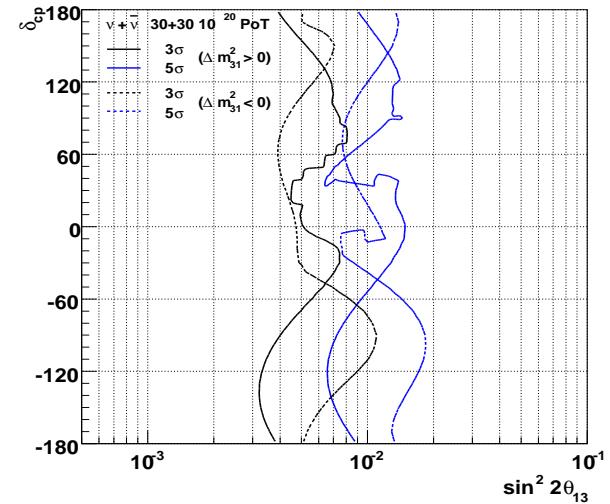
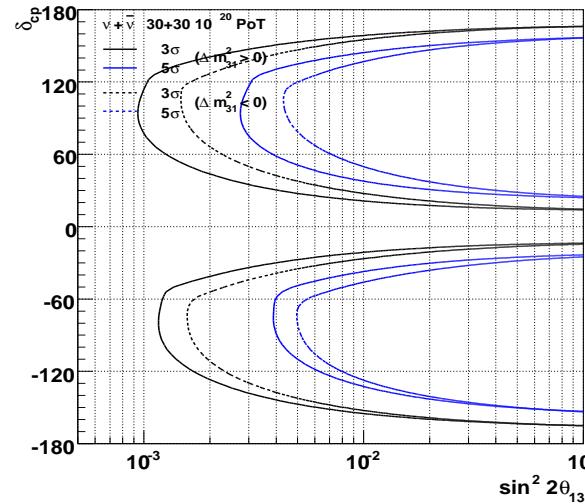
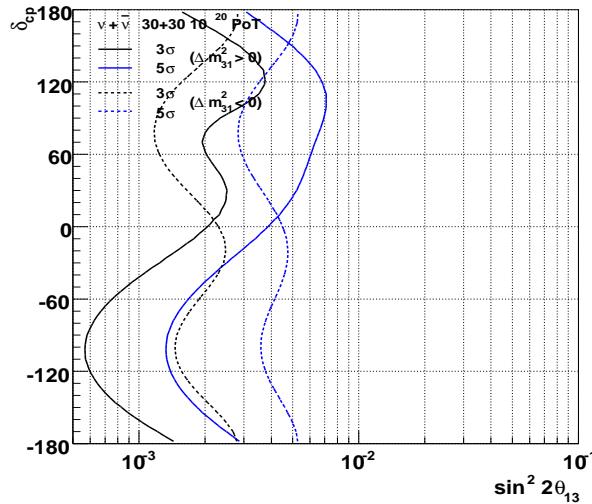
ν 60×10^{20} POT+ same for $\bar{\nu}$. WCe. 300 kT, 1.2 (2) MW, 12 (7) yrs, stat only:

only:

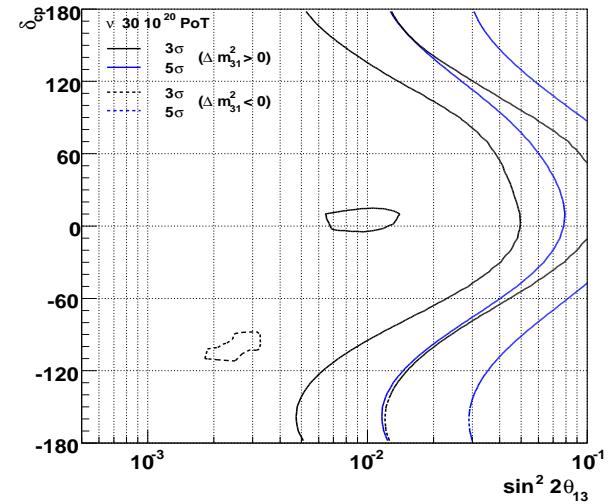
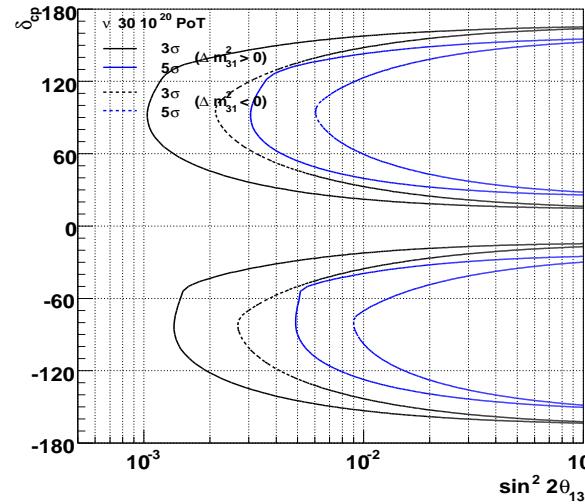
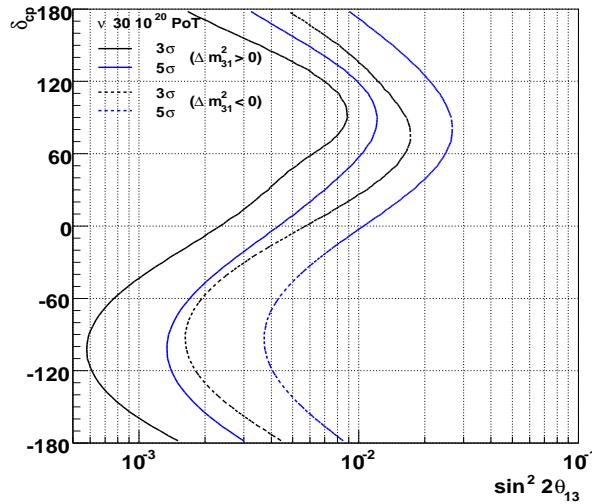


WBLE to DUSEL (1300km) + LAr

ν 30×10^{20} POT+ same for $\bar{\nu}$. LAr 100 kT, 1.2 MW beam, 6yrs, stat only:

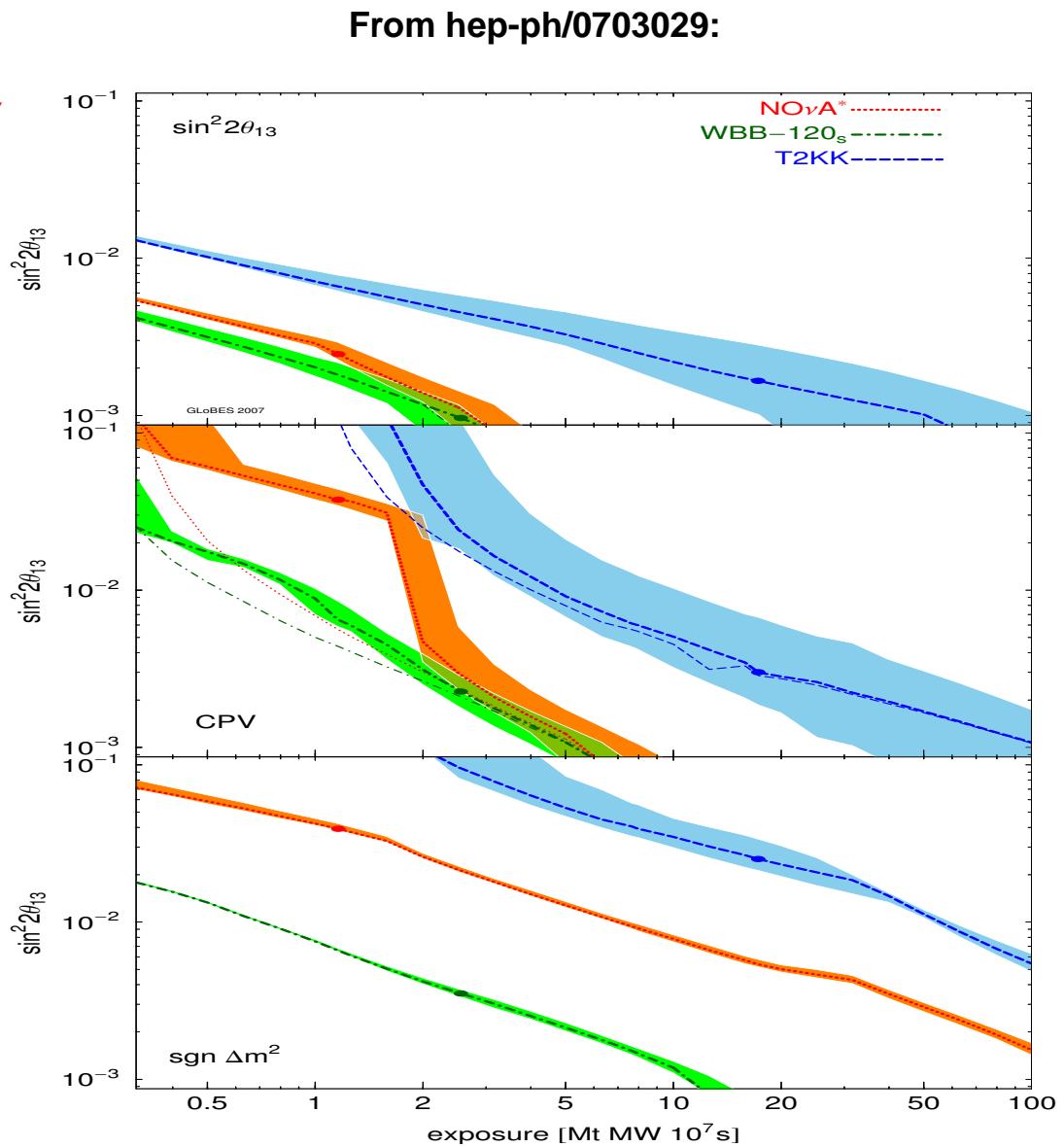
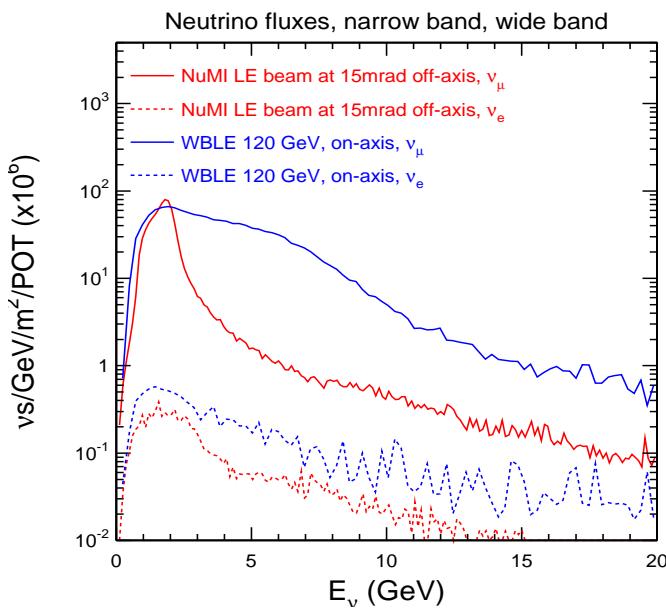


ν 30×10^{20} POT ONLY. LAr 100 kT, 1.2 MW beam, 3yrs, stat only:

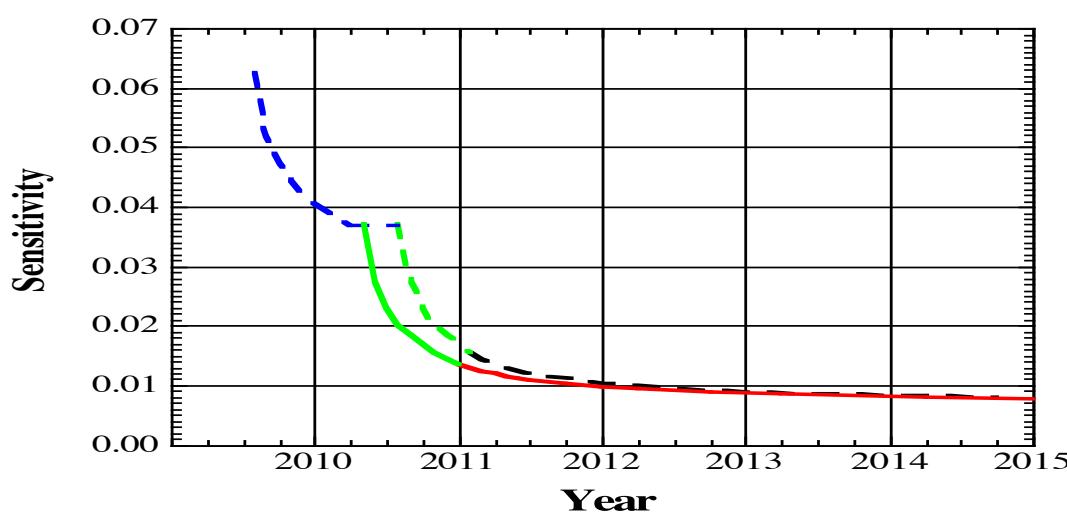


Physics Sensitivities - Compare

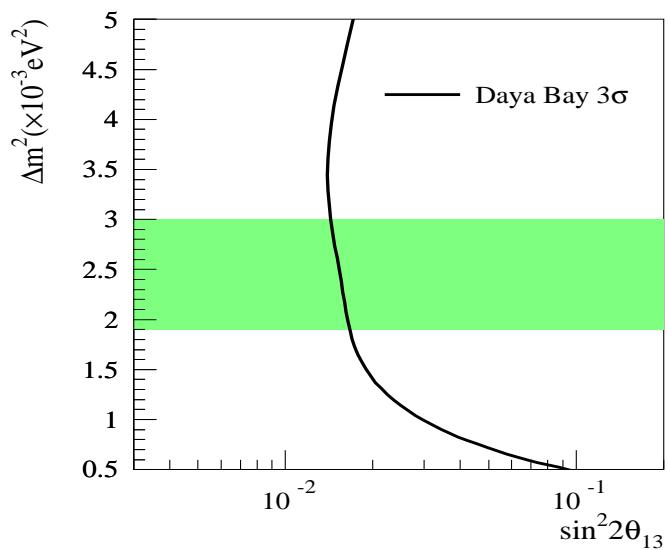
The potential physics reach from studies with the 120 GeV WBLE-DUSEL at 1300km using a LAr detector, the NO ν A* experiment and the T2KK experiment:



Daya Bay Sensitivity



Sensitivity reach at 90% CL



After 3 yrs of running

90% C.L. sensitivity limit for $\sin^2 2\theta_{13}$ at $\Delta m_{31}^2 = 2.5 \times 10^{-3} \text{ eV}^2$ for different assumptions of detector related systematic uncertainties. 3 years running for each scenario:

| Systematic Uncertainty Assumptions: | Baseline | Goal | Goal with swapping |
|-------------------------------------|----------|-------|--------------------|
| 90% C.L. Limit: | 0.008 | 0.007 | 0.006 |